Effect of heat input on the mechanical properties of high strength steel T-joints

Butt weld and fillet weld T-joints

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ABSTRACT

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ABSTRACT

The Purpose of this Bachelor's thesis was to discover, analyse and compare the differences in the behavior of different type and sizes of a t-joint welding of High strength steel (HSS). The joint sizes that were used in this thesis were ½ V-Butt weld T-joints of 8mm and 3 different sizes of Fillet weld T-joints (6mm, 10mm and 12mm). The use of this type of steel was introduced more than 30 years ago. However, sufficient data and information regarding welding parameters and behavior of this material are not presented in the EU Building codes and standards. The aim of this study was to provide information for future development and improvement in the better understanding of this product.

SSAB's Strenx 700 (S700) steel plates, measuring, with nominal yield strength of 700 MPa were used in this study. While creating the specimens, the heat input parameters were varied depending on the size of the weld and the temperature in the Heat affected zone (HAZ) was measured in the process. In addition to that, the cooling time of the metal was recorded with a Thermographic camera (infrared camera), at different points during the welding. After this, the mechanical properties of the joint were tested through the Tensile strength and the Rock-hardness test.

The results of this study show to a certain degree the effect that heat input and cooling time have on the mechanical properties of welded high strength steel. Also, we can observe the effect that welding errors have on tensile strength tests, creating discrepancies in the results. For future development regarding T-joints of high strength steel, this research can be used as a guideline.

Keywords High steel strength, weld, tensile strength, cooling time, mechanical properties, infrared camera, butt weld, fillet weld.

Pages 46 pages including appendices 20 pages

CONTENTS

1 INTRODUCTION

Steel has become one of the most used materials within the construction industry and its used has been increasing steadily throughout decades, mainly because its characteristics include: utility, versatility, design flexibility and relatively light weight while offering high strength capabilities. In addition to these, if we also take into consideration weldability, it is obvious that the high strength steel (HSS), reduces costs and offers more productivity than the mild metal used before. Having said that, due to the fact of the ever-fast advance on steel usage, the EU standards and regulations have not been able to do a thorough study of this metal's behavior up to this point.

Efforts have been made over the past decade to cover more ground toward a better understanding of the changes and behavior that the HSS goes through when it is welded. However, there are still challenges ahead to better understand what percentage of the toughness and strength of the metal is actually lost during this process. Better knowledge will give us a better outcome in the future in the use of this type of steel and how to minimize any loss of the initial properties.

This thesis can be used as a reference for further study of the way heat input influences welded HSS T-joints and their mechanical properties. The scope of this study is to offer theory correlated with experimental results involving welded S700 plates into ½ V-butt weld with a throat thickness a=8mm and Fillet welds T-joints with a=6, a=10 and a=12.

1.1 Background and theoretical framework

Welding is the most common way to merge metal parts together. In this process, heat is applied to the base metal and the filler metal which cause them to melt, ultimately, fusing them into forming a permanent bond. The quantity of heat and temperature used to form the weld joint is called heat input. Heat input is a relative measure of the energy transferred per unit length of weld. It is an important characteristic because it influences the cooling rate, which may affect the mechanical properties and metallurgical structure of the weld and the heat affected zone (Welding Innovation Vol. XVI, No. 1, 1999).

The heat affected zone (HAZ) refers to a non-melted area of metal that has experienced changes in its material properties because of exposure to high temperatures. The HAZ is identified as the area between the weld and the base metal (see Figure 1). These areas can vary in size and severity depending on the properties of the materials involved, the intensity and concentration of heat, and the process employed. Because the HAZ experiences enough heat the layer undergoes property changes that differ from the base metal. These property changes make the joint area the weakest part of the component.

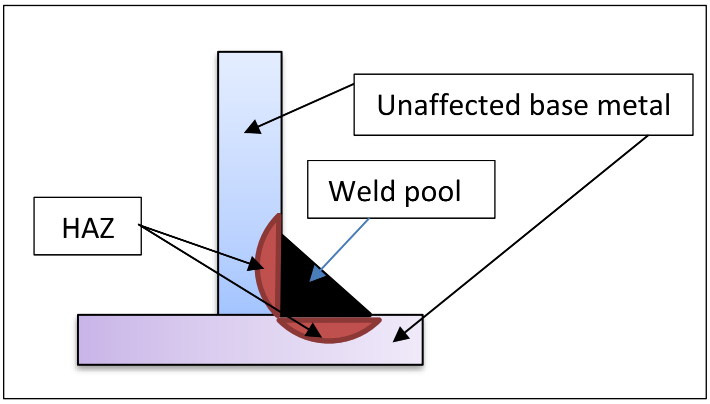

Figure 1. Heat affected zone on T-joints.

1.2 Heat Input

Heat input is directly proportional to the cooling time (see Figure 2). A higher heat input means that the cooling period will be longer allowing the microstructures of the metal to weaken up. However, if the heat input is not adequate and the cooling time is too short, weld defects may occur which can affect the behavior of the joint itself. Therefore, welding parameters are very important and the heat input, as well as the cooling time, are major factors in the process. Different sizes of weld need different heat.

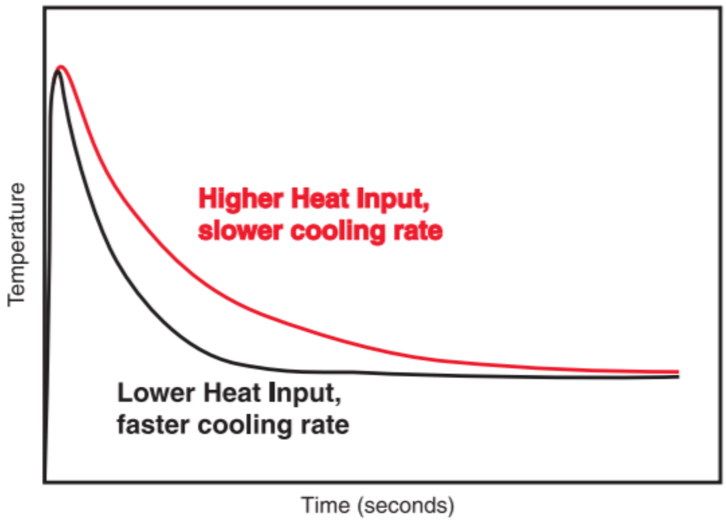

Figure 2. Heat input influences cooling time.

The heat input cannot be calculated directly. It can, however, be calculated using the Eurocodes guidelines found in EN 1011-2, Annex D [2]. See formula (1).

$$Q = \varepsilon \cdot \frac{60 \cdot U \cdot I}{1000 \cdot V} \tag{1}$$

Where U is voltage [V], I is current [A], V is the welding speed [mm/min]. The welding machine is able to gather all this data which can be analyzed later on with a computer. The coefficient ε, is the thermal efficiency and it can be taken as 0.85 for MAG welding specified in EN 1011-2 D4 [2]. From this we can see that the heat input can be controlled through voltage, and current use. Furthermore, the welding speed has an influence on the process too.

1.3 Cooling time

Once we know the heat input used we can calculate the cooling time of the metal. The most significant microstructural changes in the welded metal and the HAZ occur between the temperatures 800 °C and 500 °C. Hence the importance of measuring this part of the process. The time that takes for the metal to cool down from 800 °C to 500 °C is called cooling time better known as $t_{8/5}$, and according to EN-1011-2 equations D.2 and D.4 respectively, can be calculated using formula (2) for two-dimensional cooling time and formula (3) for three-dimensional cooling time.

$$t_{8/5} = (4300 - 4{,}3 \cdot To) \cdot 10^5 \cdot \left(\frac{Q^2}{d^2}\right)\left[\left(\frac{1}{500 - To}\right)^2 - \left(\frac{1}{800 - To}\right)^2\right] \cdot F_2 \tag{2}$$

$$t_{8/5} = (6700 - 5 \cdot To) \cdot Q \cdot \left[\left(\frac{1}{500 - To}\right) - \left(\frac{1}{800 - To}\right)\right] \cdot F_3 \tag{3}$$

Where To is the working temperature [°C], Q is heat input [kJ/mm], and d is thickness of the samples [mm]. Shape factors F_2 and F_3 can be found in EN 1011-2 [1], Table D.1, which says that can be taken as 0,9.

The selection between two or three dimensional $t_{8/5}$ is done by calculating the time using both formulas and choosing the longer time of the two results.

2 OBJECTIVES

The usual way to weld structural elements from HSS is done by a human operating a welding machine. Because of this, there are irregularities that can affect the overall performance of the specimen. Especially the welding speed is a factor causing irregularities and therefore, it is one of the parameters taken into account in the welding process. Irregularities in the welding speed can lead to significant differences at the time of measuring cooling time, depending on the weld type. However, it is inevitable and this thesis is looking for ways to have a realistic approach regarding welding done by humans

One of the objectives of this thesis is to experimentally investigate and analyze the effect that heat input has on the mechanical properties of HSS T-joints, specifically, a ½ V-butt weld and a fillet weld t-joint.

Additionally, the aim is to discover the difference in strength that exist between a butt weld T-joint and a Fillet weld T-joint in 8mm thickness steel plates S700. The butt weld will have a size of 8 mm and a 45^{o} angle bevel, while the 3 fillet welds will have sizes of 6mm, 10mm and 12.2mm respectively.

Another objective is to identify the correlation existent between the cooling time $t_{8/5}$ (the time for joint cooling from 800 ºC to 500 ºC) and the strength of the joint. To sum up, this research will provide information that could be used to optimize and develop the welding parameters, technique and capabilities of the S700 steel products.

3 TESTS ARRANGEMENTS

The High strength material used in this study is SSAB's Strenx 700 (for simplicity called S700) steel plates. The S700 is hot-rolled structural steel made for cold-forming, which meets all the requirements in EN-10149-2. All the required information about the mechanical properties and chemical composition of the material were taken directly from the manufacturer's website. see Table 1 and Table 2.

Table 1. Mechanical properties of S700.

Thickness (mm)	Yield strength R_{eh} (min MPa)	Tensile strength R_m (MPa) 6-10mm	Elongation (min %)
8	700	750-950	12

Table 2. Chemical properties of S700

C (max %)	Si (max %)	Mn (max %)	P (max %)	S (max %)	Al (min %)	Nb (max %)	V (max %)	Ti (max %)
0.12	0.21	2.10	0.020	0.010	0.015	0.09	0.20	0.15

3.1 Samples and welding

A total of 16 HSS plates will be used to conduct this experiment. All the specimens have the same measurements, 200x400x8 in width, length and thickness respectively. Two out of the 16 plates were given a single-bevel of 45° for the butt-weld T-joint specimens. See Figure 3.

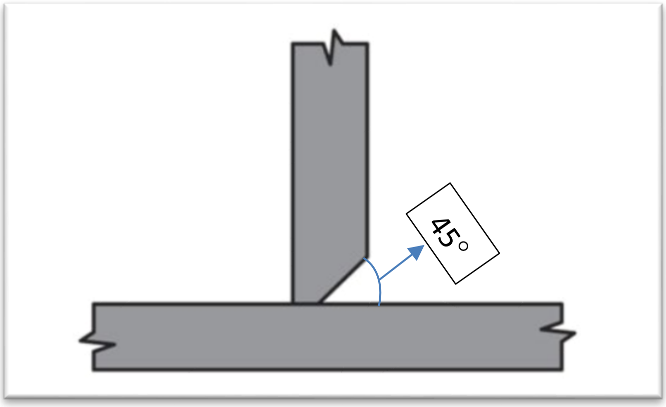

Figure 3. Butt weld T-joint single-bevelled. [TWI. Welding design website]

During welding specimens reach very high temperatures to then cool down relatively quickly to a room temperature. It is important to pay attention to the cooling time $t_{8/5}$, which is the time that takes the metal to cool off from 800°C to 500°C, as metal undergoes changes in the HAZ during this period. For this process, a Thermographic camera (infrared camera) was implemented.

The welding of the specimens was done using traditional MAG welding, in which an electric arc formed between the base metal and welding consumables causes pieces to melt forming a joint between components.

For this project, the weld types selected are butt weld and fillet weld. One of the objectives is to compare different sizes of weld and how the heat input affects their microstructural properties. Hence, we selected for the butt weld a weld size of 8mm and for the fillet weld there will be three different sizes, 6mm, 10mm and 12.2 mm. The specimens were welded in one, two and/or three weld runs. One weld runs are done with a relatively high heat input and a lower welding speed. When two and three weld runs were implemented, EN ISO15609-1: 2004 [5] and EN ISO 15612:2004 [6], are used as a guideline. However, these instructions are intended for steel grades S235, S275 and S355 only. Therefore, for S700, a much lesser heat input can be used, since the first run handles the root weld and the remaining runs can fill the groove and reach the wanted size.

The welding position was a horizontal-vertical arrangement, one plate stands on top of the other. Spot welds were done at each end of the plates to keep them in position until the main weld was done. See Figure 4.

Figure 4. Specimen for fillet weld ready to be welded.

Welding of the samples was done by Mr. Harri Nieminen from Tavastia vocational school, using as a machine a Fastmig MXF 65 arc welding machine.

The working temperature for one run weld and for the first run of the multi-run welds, was assumed to be room temperature, 23°C. For multi-run welds the specimen was left to cool off until at least 300°C. Therefore, the average working temperature between weld runs was 300°C.

Welding parameters, such as welding speed and heat input, were recorded by the welding machine. After the welding process, two butt weld T-joints with a=8mm throat thickness and a total of 6 fillet weld T-joints with a throat thickness a=6mm, a=10mm and a=12.2 respectively, were acquired.

3.2 Cooling time

For this research a thermographic camera was implemented to measure the temperature of the metal while it is being welded. It will be used to compare the results obtained with the camera to the results found while using equations D.2 and D.4 from EN-1011-2.

The above-mentioned camera used in this case was a “FLIR A325sc”. The camera was set up at about 1 meter of the specimen that was going to be welded. See Figure 5.

Figure 5. Thermographic camera ready to record temperatures.

The data analysis program used with this camera was “FLIR ResearchIR Max software”. This software allows the user to control the temperature range in which the camera will narrow down when giving results, place and arrange a specific area for the camera to focus on during the recordings, different view types and observing a live video of the whole process on a computer screen.

Before the welding process would start, three lines filled with points would be placed on the live image of the specimen, right on the expected route that will be taken by the welder when bonding the metals together. This route will have points that will record any heat coming close to them. See Figure 6.

Once the process has stopped, the program would export the results into an Excel sheet where they can be studied later on.

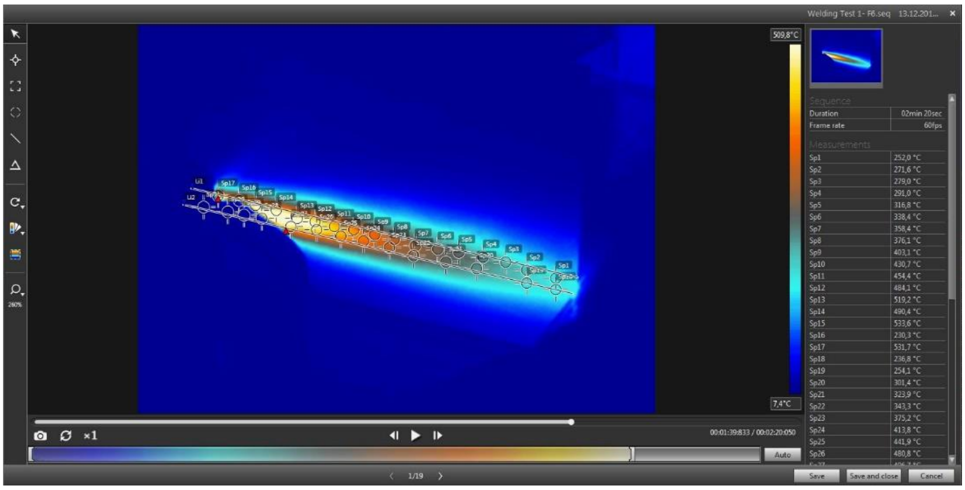

Figure 6. Screen shot of the data analysis program during a welding process.

Table 3 holds all the results both calculated and recorded by the camera and further screen shots from the software can be found in Appendix 1.

Table 3. Calculated cooling time compared to recorded cooling time.

	First run			Second run			Third run		
Name of the sample	Average working temperature	t8/5 calculated	t8/5 recorded	Average working temperature	t8/5 calculated	t8/5 recorded	Average working temperature	t8/5 calculated	t8/5 recorded
B8	23	21,4	18	-			-		
F6		38,8	18	-			-		
F10		25,5	21	100	22,5	18	100	28,5	33
F12		32,7	21		26,7	16		32,9	39

3.3 Heat input measurement

Heat input is a critical part of the process of joining two metals together. To examine the effect of the heat input used during the welding of the specimens, the level of heat input varies depending on the number of runs needed to achieve the size required. Specimens that have 2-3 weld runs, have different heat inputs starting with a higher temperature for the first run, gradually decreasing it for the second run and third run respectively.

To be able to record the heat input data, Kemppi’s ArcData catcher was implemented. Once all the welding process was completed, the ArcData catcher was connected to a computer for the analysis of the results.

The heat input measurements extracted from this device can be seen in Table 4.

Table 4 Heat input results, obtained with the ArcData catcher.

Specimen's name	Run number	Welding time (s)	Welding current (A)	Wire voltage (V)	Welding speed mm/s	Calculated heat input (kJ/mm)
B8 (Butt weld 8mm)	1	127	209.70	21.80	3.15	1.16
F6 (fillet weld 16mm)	1	97	274.9	29.3	4.12	1.56
F10	1	78	280	29	5.13	1.27
F10	2	64	258.4	29.5	6.25	0.97
F10	3	69	272.9	29	5.8	1.1
F12	1	87	283	29.2	4.6	1.44
F12	2	77	269	29.5	5.19	1.06
F12	3	22.3 (1)	283.3	29	5.38 (1)	1.18

(1) Wire ran out during welding. Only 120mm from the total 400 mm of the specimen’s length was welded.

3.4 **Tensile strength test**

New methods for tensile specimen extraction were attempted. As per usual in any project, challenges were faced in every step of the whole process. Overcoming these challenges was an important part of this case of study. The obstacles faced and the way they were surpassed, can be found in chapter 5.

From each welded specimen, T-joint shaped samples were extracted using a Cosen MH – 460M automatic band saw with a manual heavy-duty swivel head. Figure 7 shows an example of a T-joint after being extracted but it is not the actual samples used during the test because these are welded on both sides whereas the tensile test was performed with one side welded samples. In Figure 8 can be seen a sawing process as a reference of the way the samples were cut, these are not the samples used for the testing.

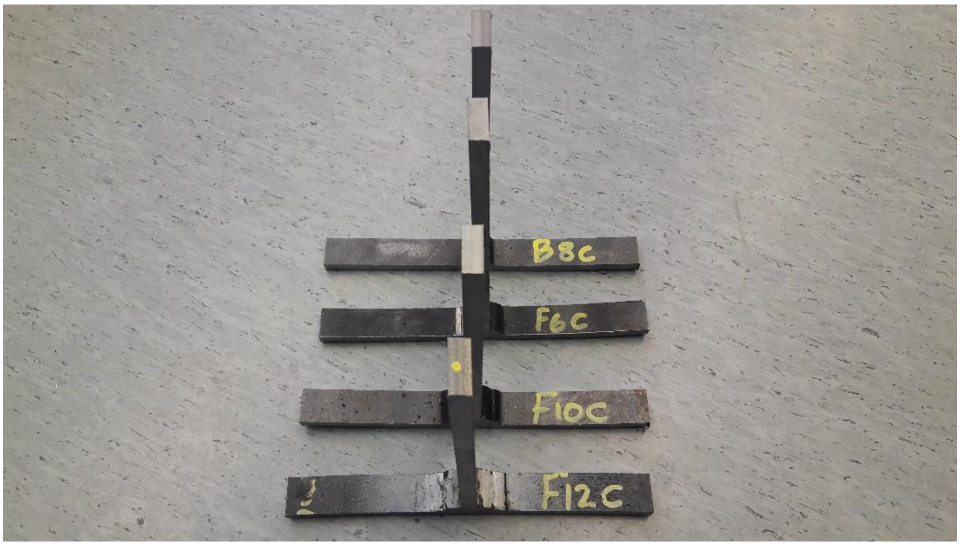

Figure 7. Example of T-joint samples after extraction. Sample not used during test. The sample presented in the figure has fillet weld on both sides of the plate. In the test, the fillet weld was only on one side.

Figure 8. Example of a sawing process for sample extraction. Sample not used during test. The sample presented in the figure has fillet weld on both sides of the plate. In the test, the fillet weld was only on one side.

Ultimately, three samples of each specimen were created. From those three samples, two were used to perform the Tensile strength test and the last one remaining was used for the Hardness test. Each specimen had a different weld size, which means that every size has three samples to perform the above-mentioned tests.

All the specimens welded have the same measurements. These are 200mm in width, 400mm in length and 8mm in thickness. Along the length of the specimen (400mm) the samples were cut out about every 20mm, thus, changing the width. The exact dimensions can be seen in Figure 9 in detail. However, this picture shows a sample welded on both side but the samples used for the tests were welded only on one side. Figure used only as a reference.

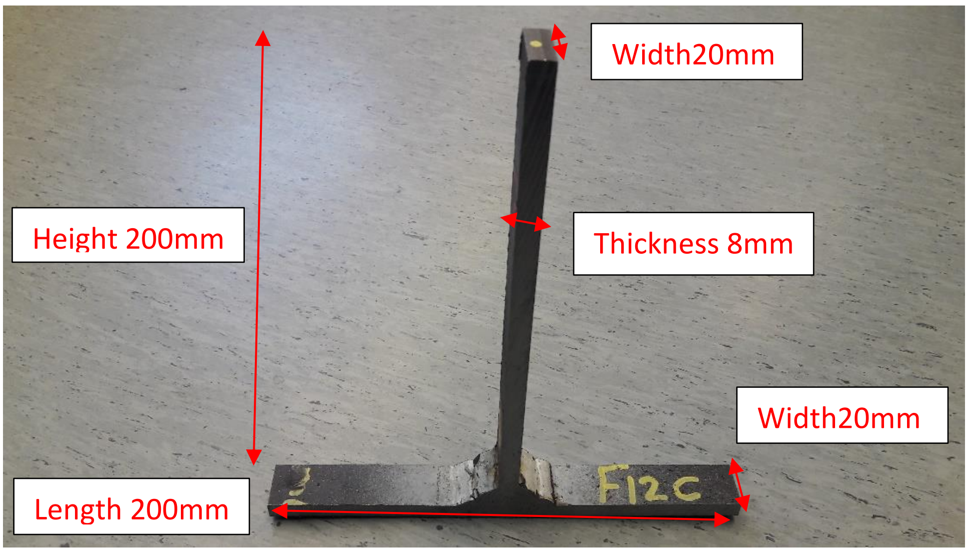

Figure 9. Example of Dimensions of the samples created. Sample not used during test. The sample presented in the figure has fillet weld on both sides of the plate. In the test, the fillet weld was only on one side.

Table 5. Final test samples.

Name of sample	width of chord element	Average length of chord element	Width of vertical element	Average length of vertical element	Average thickness of element	Number of weld runs	Type of weld
B8-1	19.7	200mm	19.8	200mm	8mm	1	Butt weld 8mm
B8-2	19.6		19.7				
F6-1	19.7	200mm	19.6	200mm	8mm	1	Fillet weld 6mm
F6-2	19.8		19.9				
F10-1	19.9	200mm	19.6	200mm	8mm	3	Fillet weld 10mm
F10-2	19.8		19.8				
F12-1	19.6	200mm	19.8	200mm	8mm	3	Fillet weld 12mm
F12-2	19.7		19.7				

3.4.1 Tensile test arrangement with Zwick Roell Z250

The shape presented by the samples made it impossible to arrange the tests normally. To solve this issue further planning and development was necessary. The solution reached was to create a test jig that would take the sample and place it comfortably inside the claws of the tensile strength testing machine. However, there are some factors that need to be taken into account when manufacturing such an artefact. For instance, the jig should be able to withstand twice the maximum load expected and at the same time it cannot be too big for handling reasons. Furthermore, it should be able to limit or, in the best case, eliminate completely horizontal the slippage of the sample.

After making an analysis of the situation, calculations were necessary to support the theory. To find the maximum expected force during the test, it was necessary to use the ultimate strength of the material, 800 N/mm^2, and the cross-sectional area of the tensile sample, 160mm^2 (20mm x 8mm). With this information it is possible to estimate the maximum force possible, 128 kN. The next step was to run some tests with the jig to see its behaviour and ultimately designing the final product which can be seen in Figure 10.

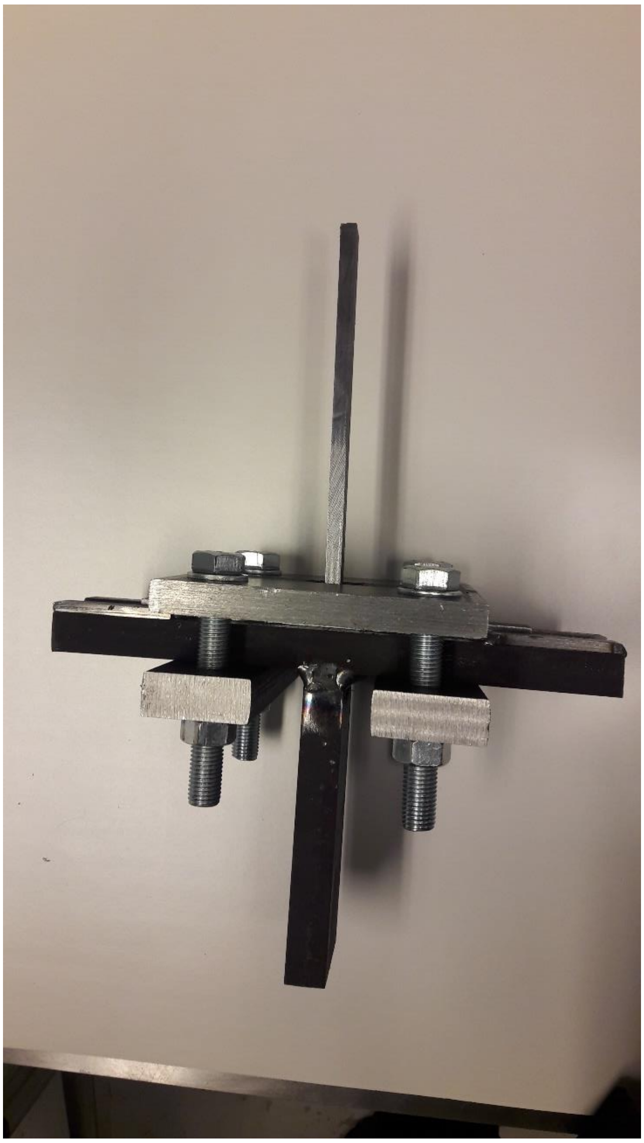

Figure 10. Test jig with sample included ready to be tested.

The jig consists of two parts, the base, where the sample rests and the bracing part that holds the sample in place and allows no movement during the tensile test. The base plate has two plates (20mm thickness each) welded together forming a T-joint, resembling the shape of the very sample. Additionally, there are four barricades on top of the base to avoid any lateral movement during the tensile strength test. The components of bracing include a steel plate, with a thickness of 15mm, with a hole located at the centre of it. To lock the sample in place there are four steel bolts long enough to go through the bracing plate and two smaller plates located below and on each side of the base plate. The bolts are tightened at a force of 200 N. The exact dimensions and parts of the test jig can be seen in Figure 11 and Figure 12. The parts can be differentiated by color. The dark metal color is the base and in a brighter color, the bracing parts can be observed.

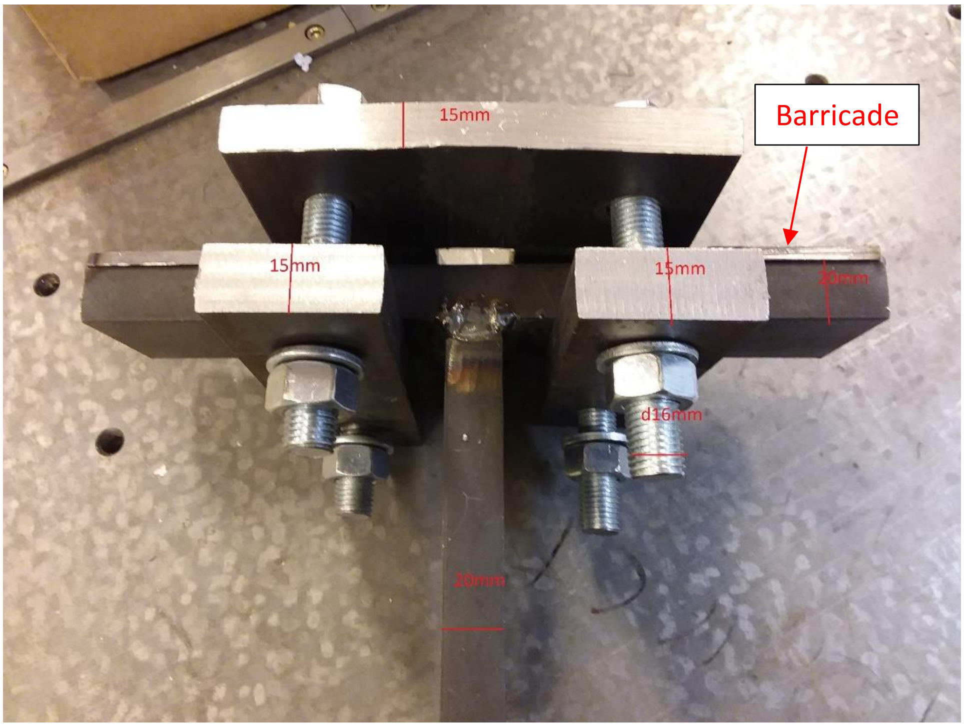

Figure 11. Test jig dimensions and parts, side view.

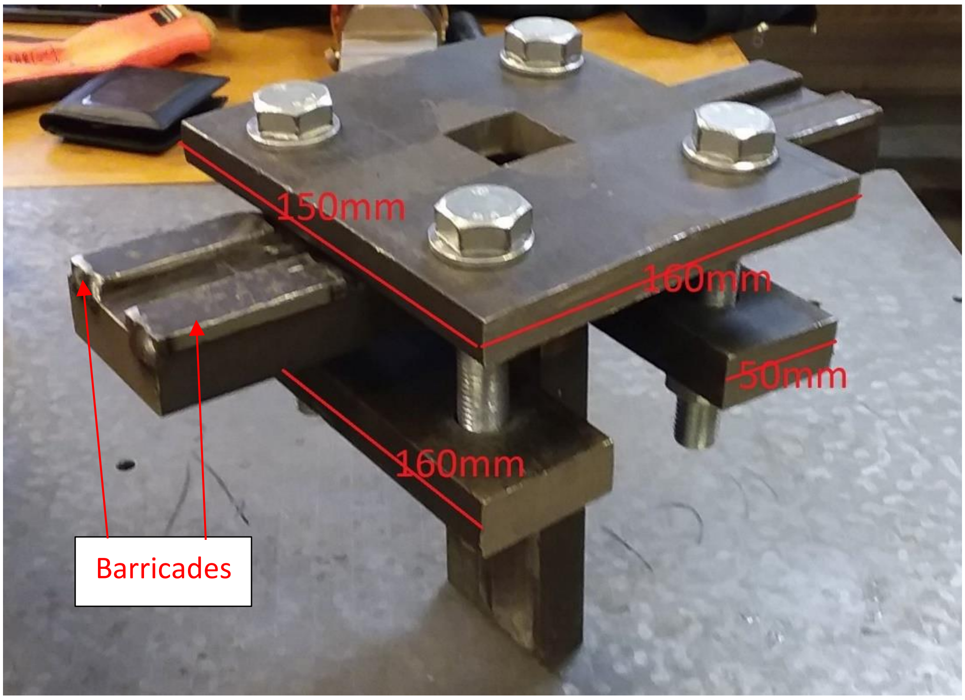

Figure 12. Test jig from a top view

Once the jig and the sample are placed in the machine, the test is ready to start. Figure 13 shows the test arrangement and the starting position for the test.

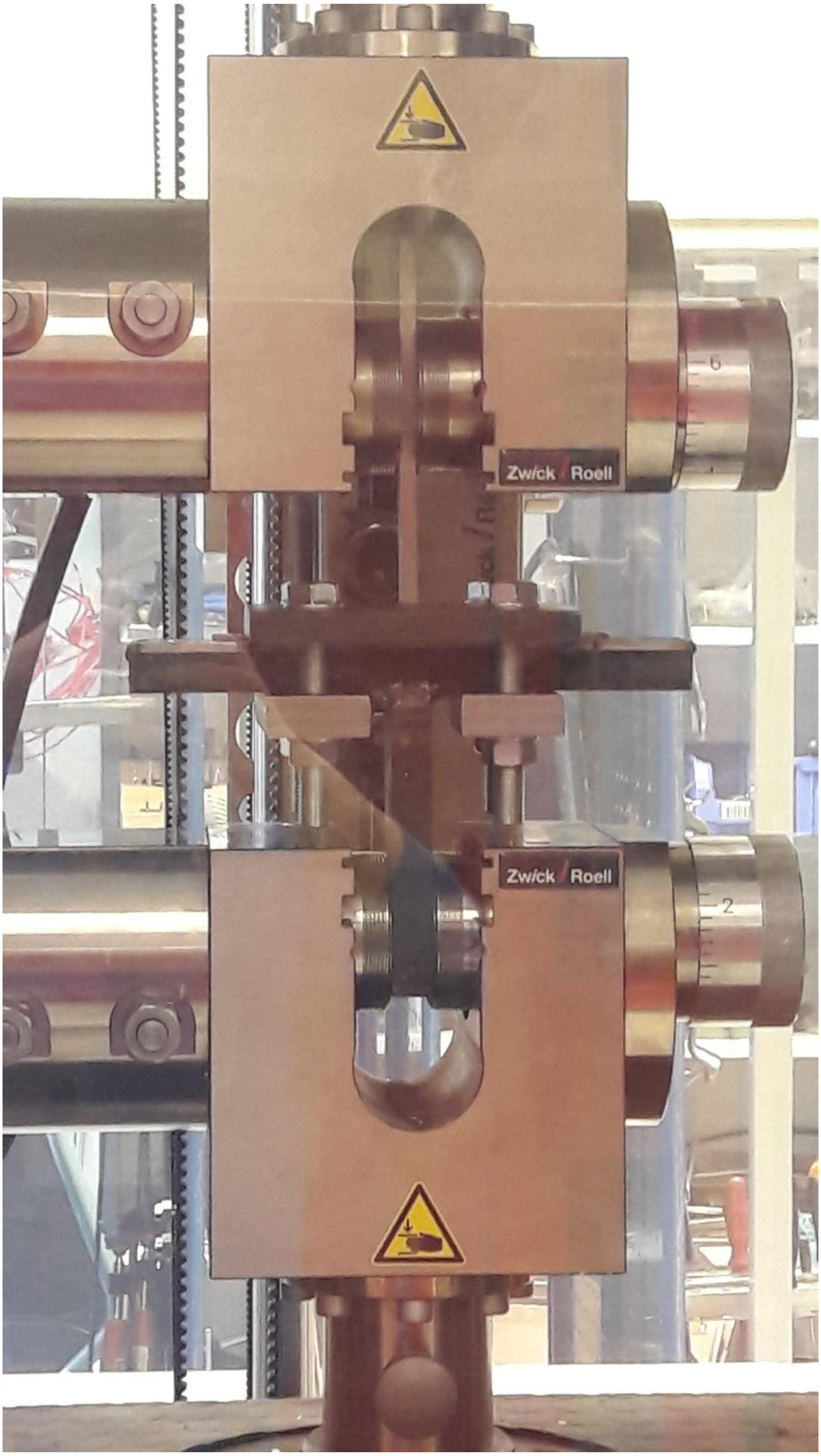

Figure 13. Testing machine with testing jig and sample in place.

3.5 Hardness test

Hardness is a characteristic of a material, not a fundamental physical property. It is defined as the resistance to indentation, and it is determined by measuring the permanent depth of the indentation.

More simply put, when using a fixed force (load)* and a given indenter, the smaller the indentation, the harder the material. Indentation hardness value is obtained by measuring the depth or the area of the indentation using one of over 12 different methods.

Hardness testing is used for two general characterizations

Material Characteristics
- Test to check material
- Test hardenability
- Test to confirm process
- Can be used to predict Tensile strength

Functionality
- Test to confirm ability to function as designed.
- Wear Resistance
- Toughness
- Resistance to impact

The type of material and expected hardness will determine the test method. Materials such as hardened bearing steels have small grain size and can be measured using the Rockwell scale due to the use of diamond indenters and high PSI loading. Very small parts or small sections may need to be measured on a microhardness tester using the Vickers. (Newage testing instruments, www.hardnesstesters.com)

For this study the Vickers pyramid test was used to measure the hardness of the material.

The Vickers method is based on an optical measurement system. The Microhardness test procedure specifies a range of light loads using a diamond indenter to make an indentation which is measured and converted to a hardness value. It is very useful for testing in a wide type of materials, but test samples must be highly polished to enable measuring the size of the impressions. Figure 14 and Figure 15 show examples of impressions on any surface and on a metal observed through a microscope, respectively. A square base pyramid shaped diamond is used for testing in the Vickers scale. Typically loads are very light, ranging from 10gm to 1kg.

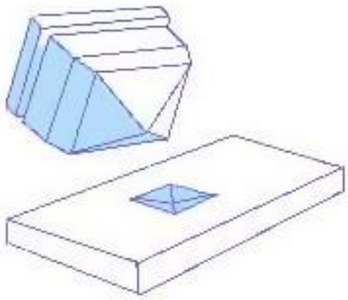

Figure 14. Example of a Vickers test print on a material’s surface.

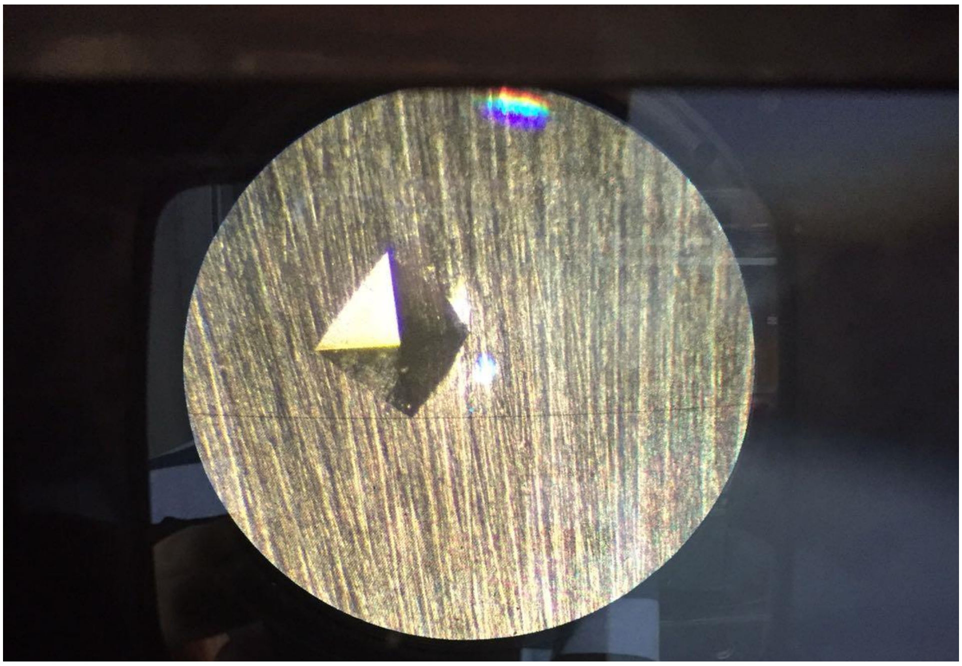

Figure 15. Real image of a diamond shape square print on a metal surface.

To complete these tests, a set of samples taken from the specimen for the hardness test were cut in small pieces closed to the welded area. This way, they could be easily handle on a Vickers tester and a microscope. A total of eight points were chosen to complete the tests. Figure 16. Vicker’s tester used to create prints on metal pieces.

Figure 16. Vickers tester used for hardness test.

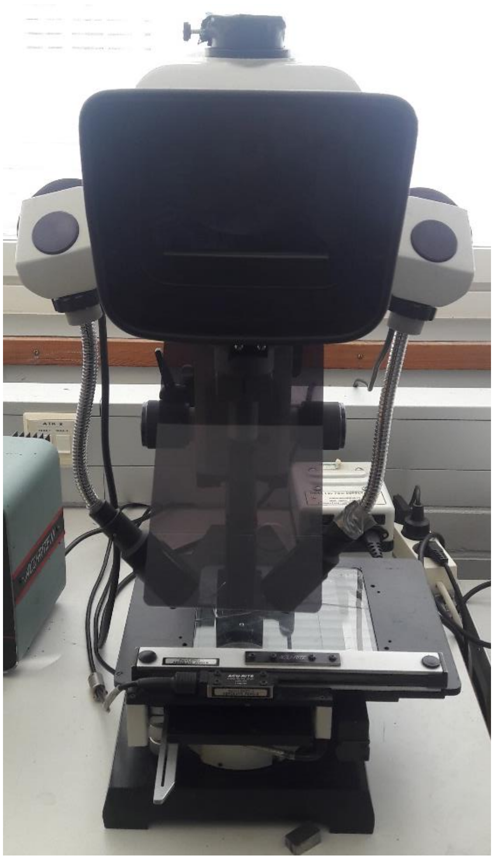

Figure 17. Microscope used to measure the diamond-shaped impressions.

4 RESULTS

4.1 Tensile strength test results

For comparison purposes, Ultimate shear force of the material was taken as F_u=750 N/mm^2. Tensile test graphs can be found in Appendix 2 and photographs of the failure modes are presented in Appendix 3. Table 3 summarizes the tensile test results for these studies.

Table 6. Cooling times and tensile test results.

Name of sample	Heat input	t8/5 calculated	t8/5 recorded	Max. Shear force	Ultimate shear strength calc.	Ultimate shear strength of material	Strength capacity	Failure mode
	[kJ/mm]	*S*	*S*	[kN]	[N/mm2]	[N/mm2]	%	
B8-1	1.16	21	18	57.2	357.5	433	82.6	Weld
B8-2	1.16	21	18	74.4	465		107.4	Weld
Average	**1.16**	**21**	**18**	**65.8**	**411.3**		**95**	**-**
F6-1	1.56	39	18	63.5	396.9	433	91.7	Weld
F6-2	1.56	39	18	71.0	443.8		102.5	Weld
Average	**1.56**	**39**	**18**	**67.3**	**420.4**		**97.1**	**-**
F10-1	1.11*	26*	24*	52.3	326.9	433	75.5	Chord
F10-2	1.11*	26*	24*	46.4	290		66.9	Chord
Average	**1.11**	**26**	**24**	**49.3**	**308.5**		**71.2**	**-**
F12-1	1.23*	31*	25*	43.8	273.8	433	63.23	Chord
F12-2	1.23*	31*	25*	67.6	422.5		97.6	Chord
Average	**1.23**	**31**	**25**	**55.7**	**348.2**		**80.4**	**-**

*Average for the samples with 3 weld runs.

The calculated ultimate shear strength value was obtained using the maximum shear force divided by the cross-sectional area of each tensile sample.

The ultimate shear strength of the material came from the formula $\frac{Fu}{\sqrt{3}}$ found in the European standards EN 1993-1-8 § 4.5.3.3-4.

The shear strength capacity of the welded joints was compared to the base material to obtain a percentage.

According to the theory, fillet welds of 10 and 12 mm, which were welded with an average lower heat input and multiple run welds, should have a higher resistance and strength that the fillet weld of 6mm. However, as can be seen in Table 6, this is not the case. Even though the fillet weld with a 6mm size (F6-1 and F6-2) has a higher heat input and were done by a single run weld, it possesses a significant higher average shear strength and a lower cooling time than the fillet weld with a 10mm and 12mm size (F10-1, F10-2, F12-1 and F12-2).

Table 6 has other inconsistencies between values of samples obtained from the same welded specimen. For example, we can observe that samples B8-1 and B8-2 (Butt weld 8mm) have a different maximum shear force, even though they were extracted from the same welded specimen. This can be attributed to welding errors. One error could be insufficient heat input. This can affect the weld making the joint of base metal with the weld pool difficult, creating an incomplete fusion of metals. Figure 20 shows an example of incomplete fusion on a butt weld sample.

Another possibility is the change of welding speed within the same weld run. If the speed is not constant, this can create differences depending on the location where the samples were cut from. This change can create a lack of root penetration and leave gaps between the weld and the base metal, weakening its properties and strength ultimately affecting the outcome of the tensile strength test.

Figure 18. Tensile test butt weld specimen after failure.

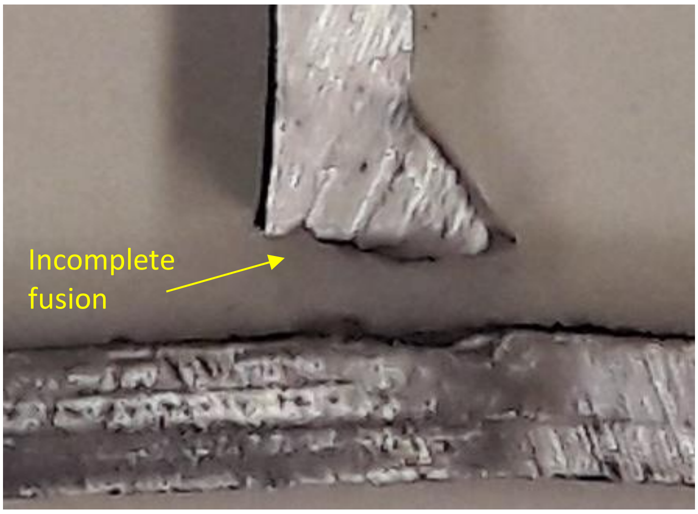

Figure 19. Magnified image of the failure.

Table 6. A summary of the tensile strength test results.

Number of weld runs	Average Heat input	Average t8/5 calculated	Average t8/5 recorded	Average Max. Shear force	Average max. shear stress
	[kJ/mm]	*S*	*S*	[kN]	[N/mm2]
1	1.36	30	18	66.5	415.8
3	1.17	28.5	24.5	52.5	328.3

4.2 Hardness test result

The location of the points on the samples used to develop this test can be observed in Figure 21 to Figure 22.

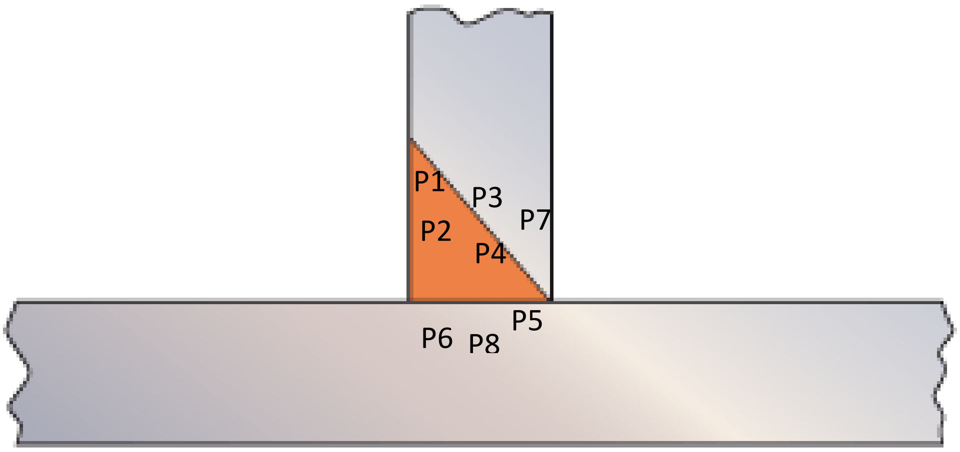

Figure 20. Location of points on the butt weld 8mm.

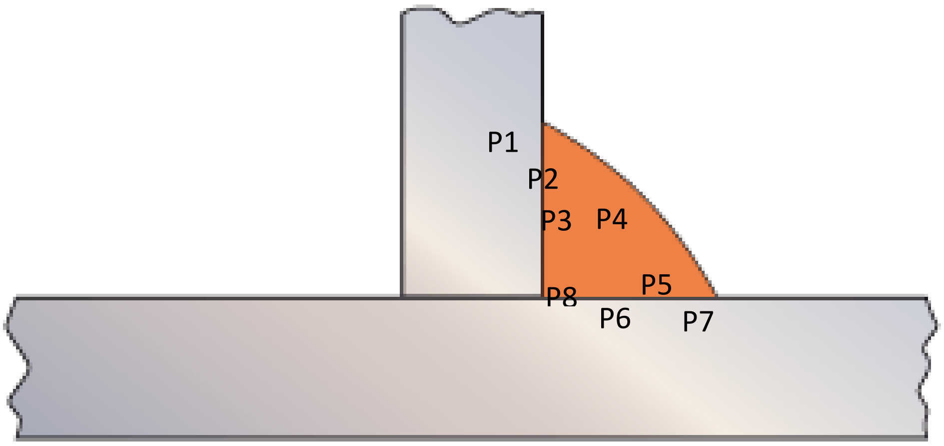

Figure 21. Location of points on the fillet weld 6mm.

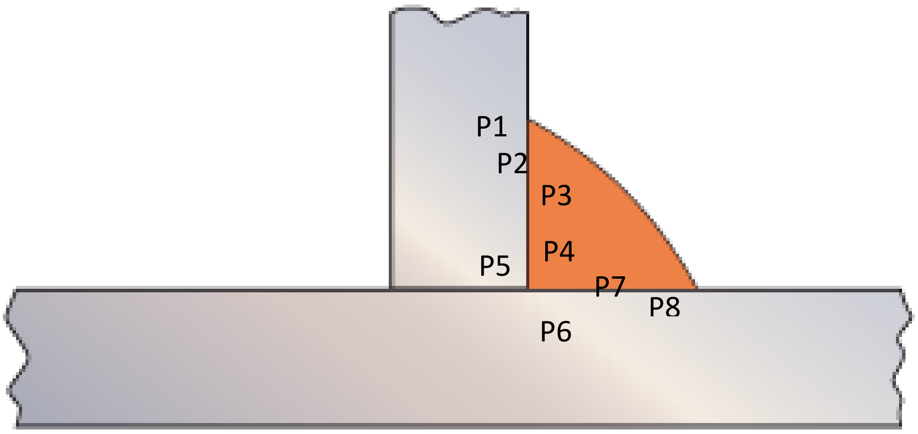

Figure 22. Location of points on the fillet weld 10mm.

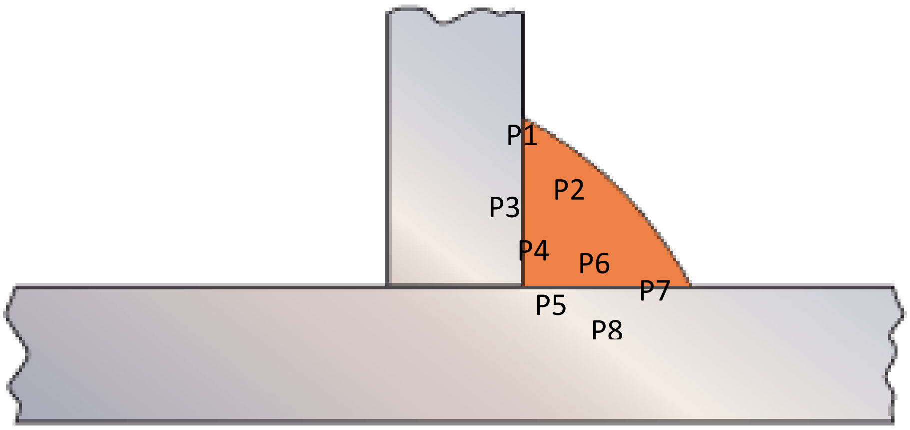

Figure 23. Location of points on the Fillet weld 12mm.

Table 7 lists the results obtained during the hardness test of the samples.

Table 7. Hardness test results.

Sample B8			Sample F6			Sample F10			Sample F12		
Spot	Hadrness value	Number of weld runs	Spot	Hadrness value	Number of weld runs	Spot	Hadrness value	Number of weld runs	Spot	Hadrness value	Number of weld runs
P1	253	1	P1	269	1	P1	266	3	P1	258	3
P2	249		P2	220		P2	219		P2	254	
P3	225		P3	229		P3	235		P3	198	
P4	235		P4	232		P4	251		P4	221	
P5	225		P5	229		P5	260		P5	213	
P6	259		P6	224		P6	275		P6	225	
P7	251		P7	224		P7	240		P7	223	
P8	268		P8	237		P8	227		P8	271	

Table 8. Average hardness arranged by number of weld runs.

Spot	Average Hadrness value	Number of weld runs	Spot	Average Hadrness value	Number of weld runs
P1	261	1	P1	262	3
P2	235		P2	237	
P3	227		P3	217	
P4	234		P4	236	
P5	227		P5	237	
P6	242		P6	250	
P7	238		P7	232	
P8	253		P8	249	

In some readings, one or more measured values can differ amongst the results on the same region. This happens because, the indentation used on Vickers hardness test is considerably small. Hence, hardness test reading can be taken from different grains. In this case, there is the possibility of taking measurements from different grains or a combination of both, resulting in a high deviation value. Thus, it is recommended to conduct further investigation, for instance on macro-hardness test, to avoid the high deviation in the measured values.

Comparing the hardness test result between each weld set (one run and three run welds), samples welded using one weld runs shows approximately the same hardness value as the welds done with three run welds. This shows that the heat input used, during welding of samples with one weld run, was too low. Usually welds done with one run have a longer cooling time weakening the metal on the Heat affected zone (HAZ). Welds that are made with two or more runs should have a lower heat input than those having single run welds, which should create a faster cooling time for the metal. Thus, allowing the metal to conserve more hardness than the welds done by one run. Figure 23 presents the relation between the cooling time and the hardness value in different zones of the welded joint.

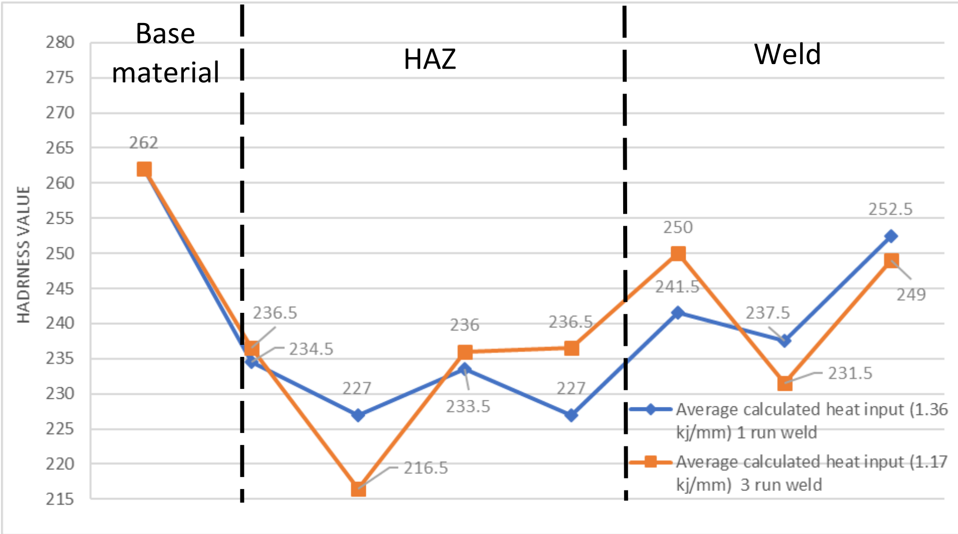

Figure 24. Heat input vs Hardness

The Figure 26 below illustrates how heat input can affect the hardness value of a welded joint with respect to the base material value.

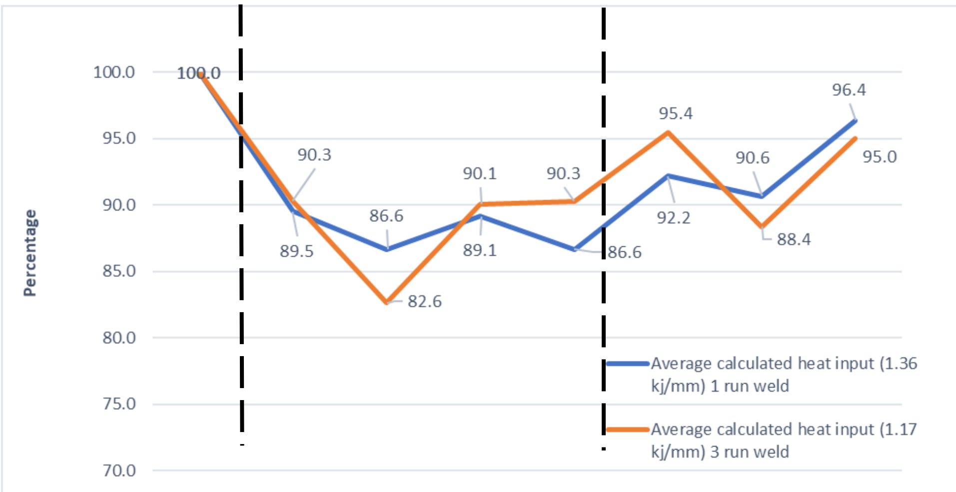

Figure 25. Hardness values about the base material.

in Figure 26 we can clearly see that the smallest percentage is found in the heat affected zone (HAZ) of the three run welded joints. On top of that, for samples with a longer cooling time, the hardness value dropped as low as 83% relative to the base material hardness value. For samples with a shortest cooling time, the lowest value is 87% compared to the base material.

To sum up, the samples with the shortest cooling time have the indicators of a higher hardness value. In this case, the samples with one run weld have a highest hardness value than the samples with three run welds which should not happen. The data recorded by the infrared camera does not resemble the results expected.

5 CONCLUSIONS AND RECOMMENDATIONS

This thesis confirms that regarding welding of HSS, the heat input and cooling time are big factors affecting the tensile strength and hardness of welded steel joints.

The results show discrepancies amongst samples extracted from the same specimen. Because the samples came from the same specimen, they should have similar values but we can clearly see that this is not the case. Even though samples share the same cooling time, they do not share the same hardness values, thus affecting their overall performance under the tensile strength test. The comparison between samples of the same welding type, the same weld size and the same cooling time, shows a big percentage difference amongst each other. Taking for instance the samples with a fillet weld size 12mm, F12-1 has an ultimate shear strength of 273.8 N/mm while F12-2 has a 422.5 N/mm. The percentages show this huge difference with the former having a 63.23% strength capacity and the latter 97.6% compared to the base material. It can be established that factors such a heat input, welding speed and cooling time have a critical role determining the effect of a weld over the mechanical properties of steel. Hence, this research was made to confirm the changes within the microscopic structures of the metal. To obtain a better result out of the HSS when being welded, heat input and cooling time need to be monitored closely. Paying attention to possible weld errors proves to be important because it can directly affect the tensile strength of the metal.

Regarding the hardness of the metal, it was observed that the lowest hardness value was, as expected, found in the Heat Affected Zone (HAZ) of all the samples. This confirms the premise that the HAZ is the most critical point when welding High Strength Steel (HSS) joints.

The samples that perform better in the tensile strength test, were those samples with a faster cooling time. Therefore, confirming the idea that shorter cooling time gives a less time for the crystal structure to transform. For this study the discrepancies make difficult the comparison of weld of different sizes due to the variety of results.

This research is limited to welding parameters measurements and strength properties of HSS welded joints of steel with the yield strength 700 MPa. Further research may be carried out to investigate the behaviour of HSS T-joints.

As a recommendation, the use of an infrared camera as a heat measurement it is not very reliable. Factors such as angle of the recordings and distance may influence the readings and timing of the welding process. Further development of this technique is required. Also, screening can become a problem when someone is performing the welding. This person could come across the view of the camera consequently affecting the heat readings. Hence, the angle and distance are important when planning to use this method for reading the heat and calculating the cooling time of the specimens during a welding process.

Furthermore, for this study, a single specimen of each weld size was used for the extraction of two samples. This makes the samples that have a single run weld, the same heat input and the same cooling time. More specimens and more samples should be created for a single test. This will allow to have different heat input, hardness, and cooling time values which can facilitate to spot discrepancies and errors.

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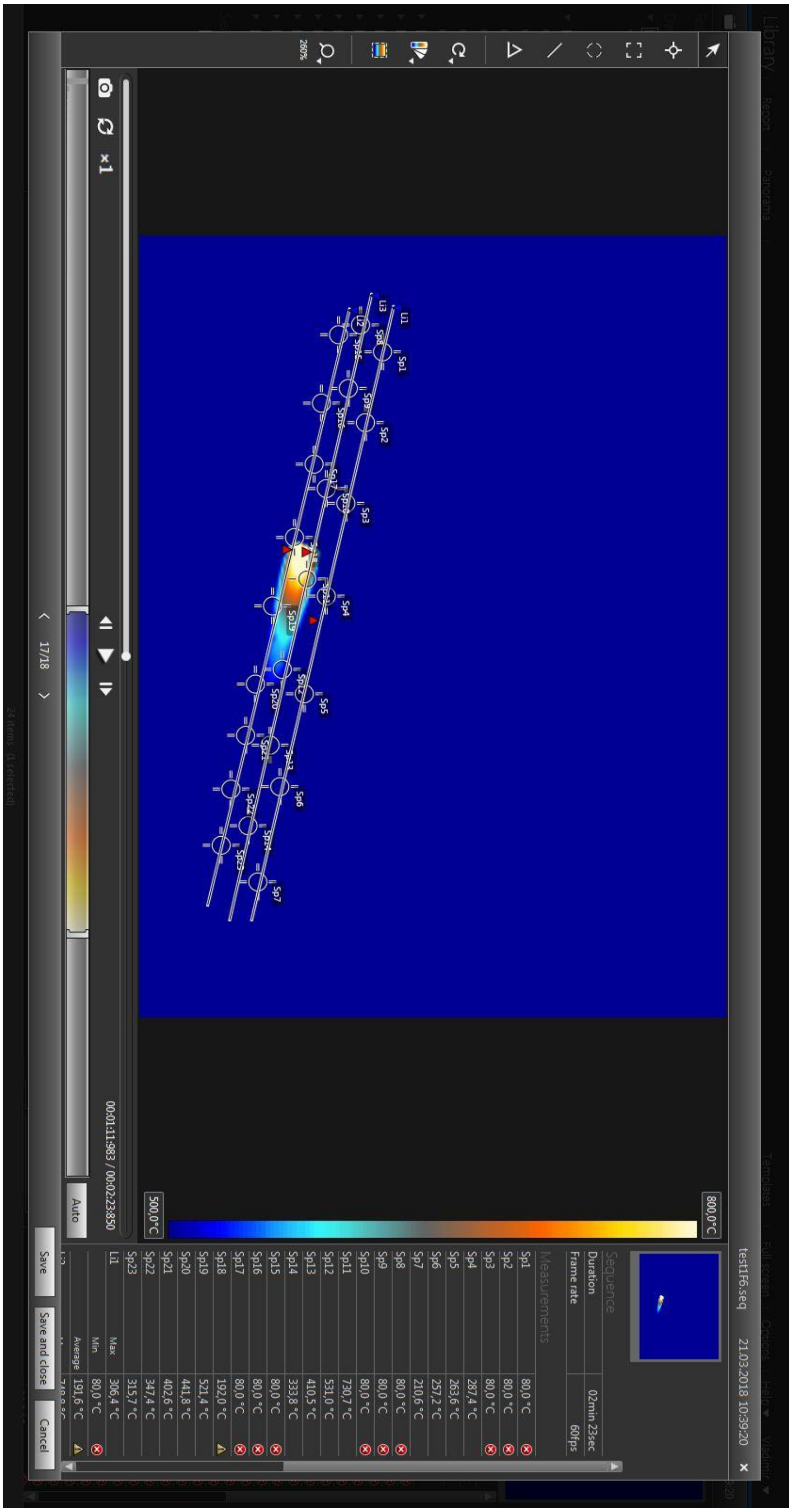
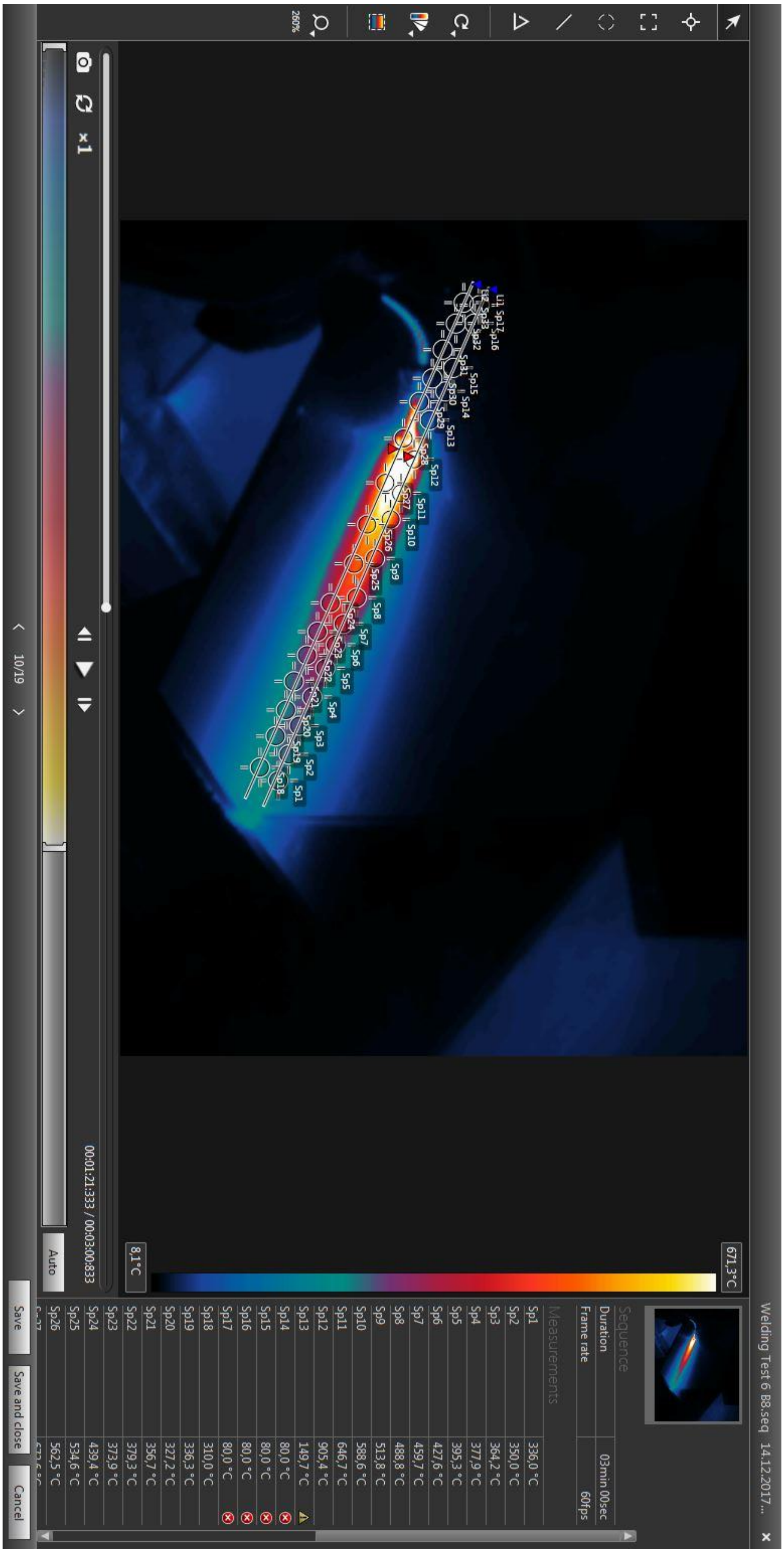
Appendix 1

COOLING TIME PICTURES

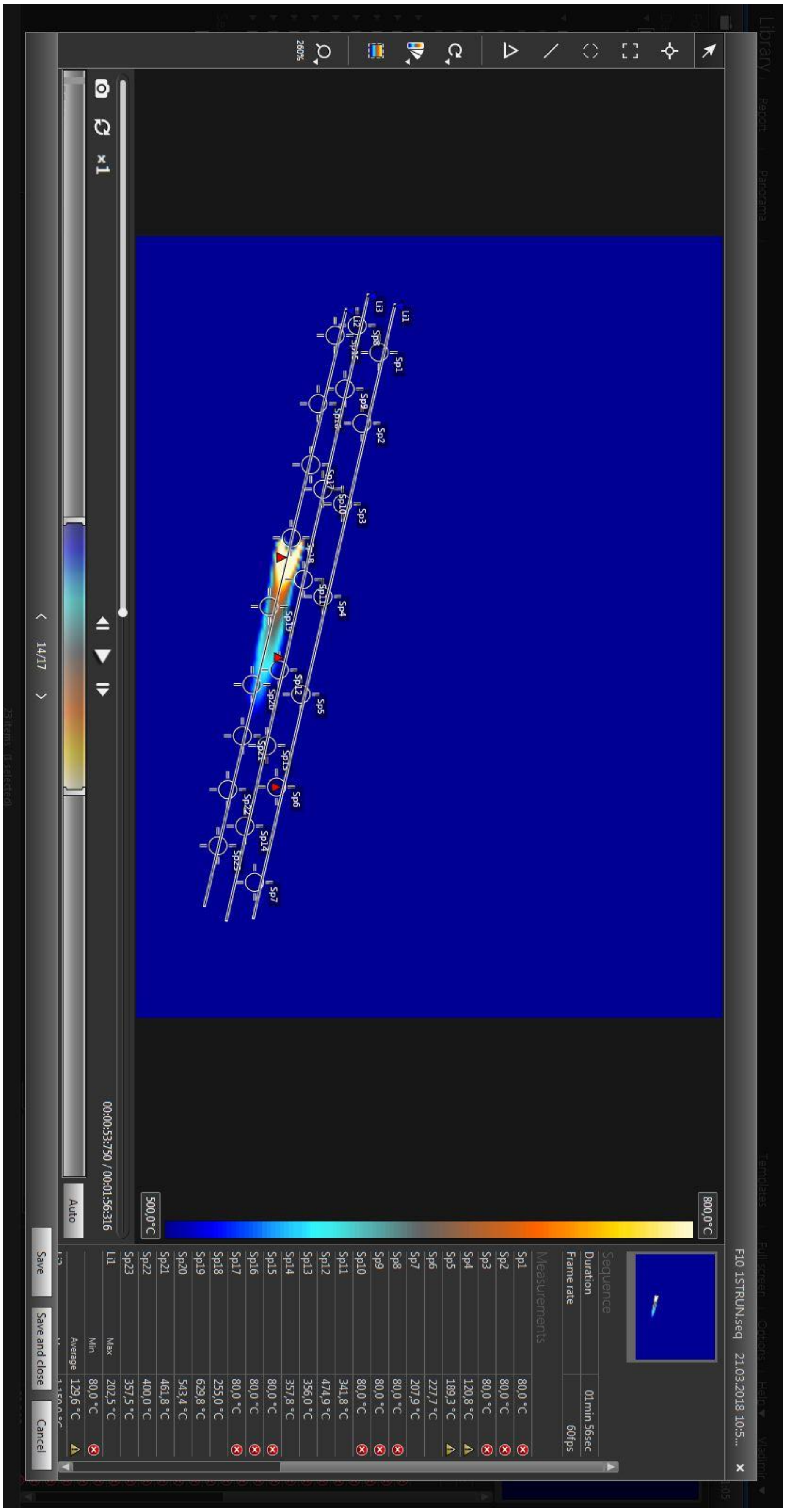
Fillet weld 6mm (F6)



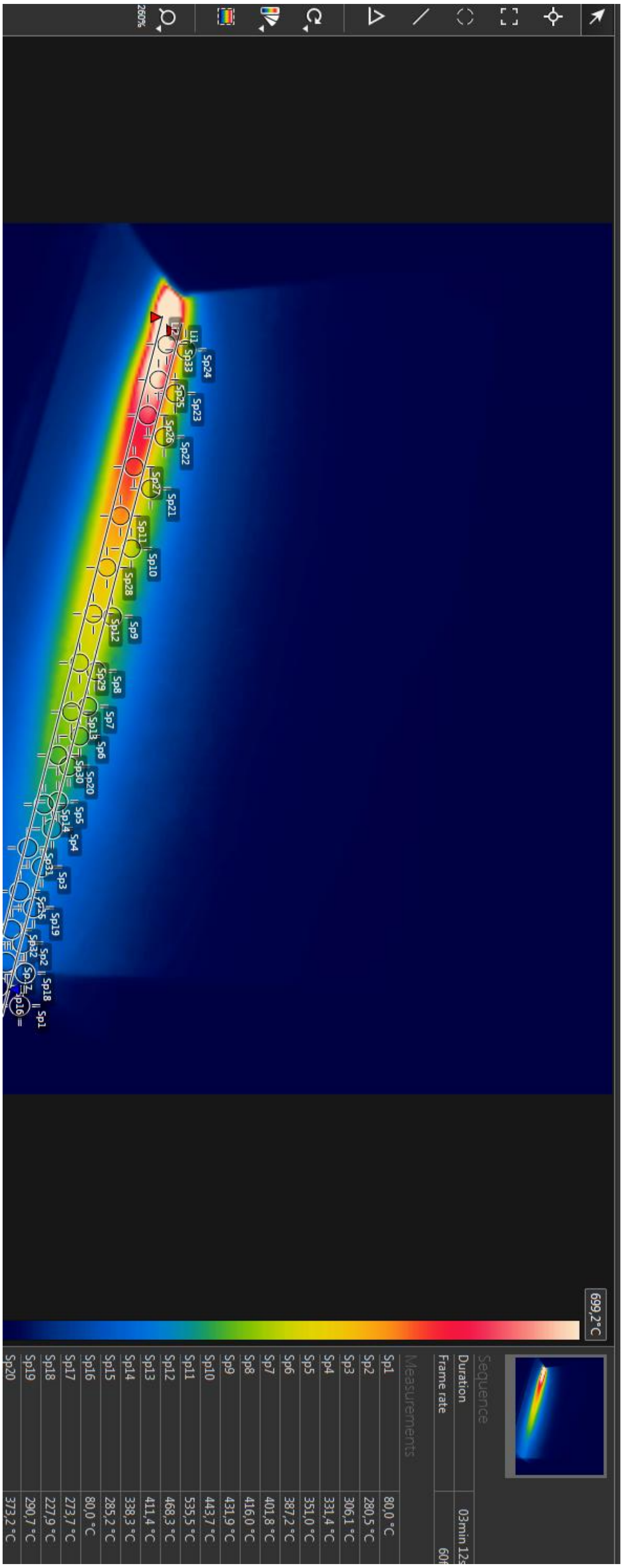
Butt weld 8mm (B8)



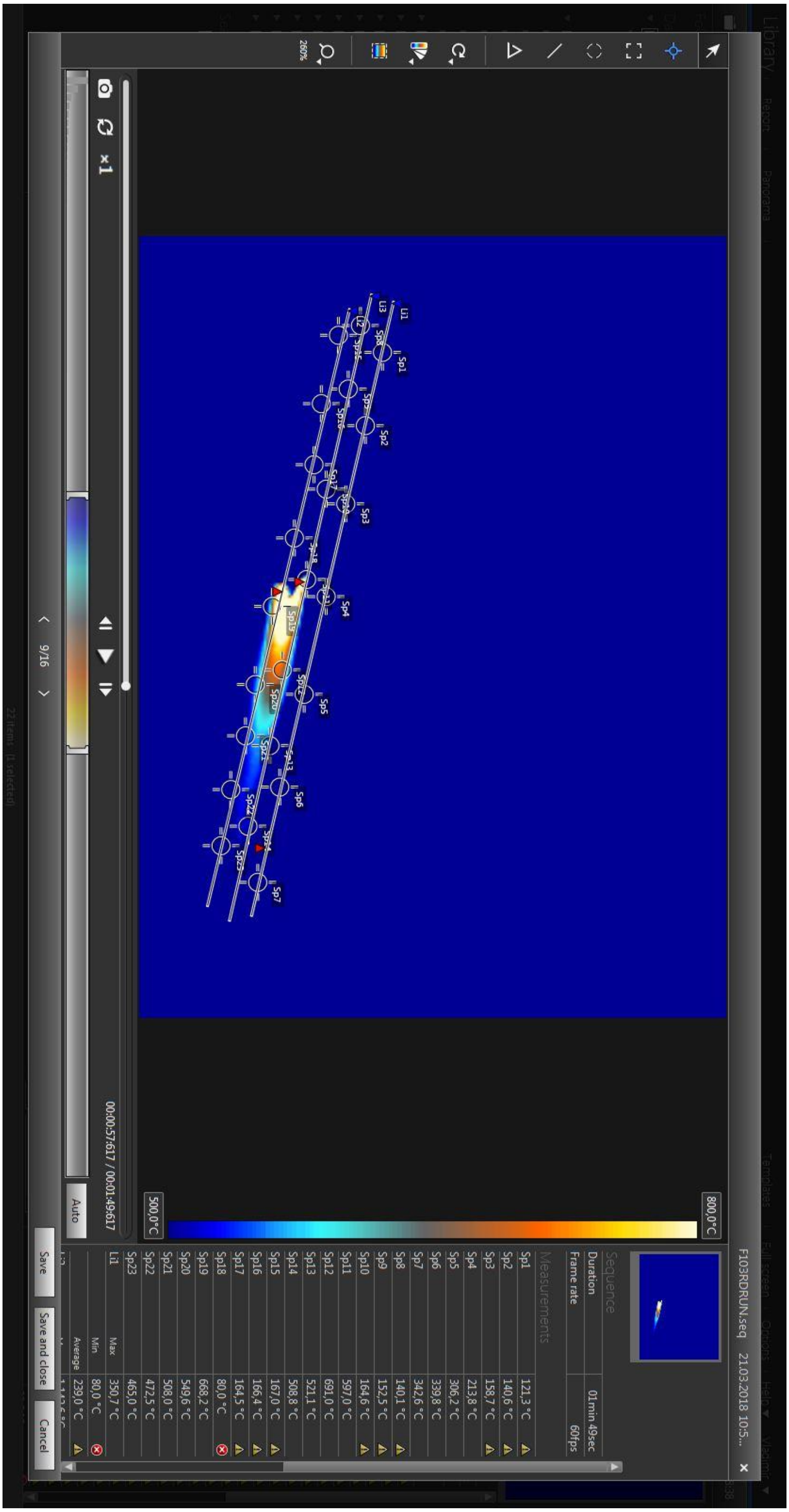
Fillet weld 10mm, 1^{ST}. RUN (F10)



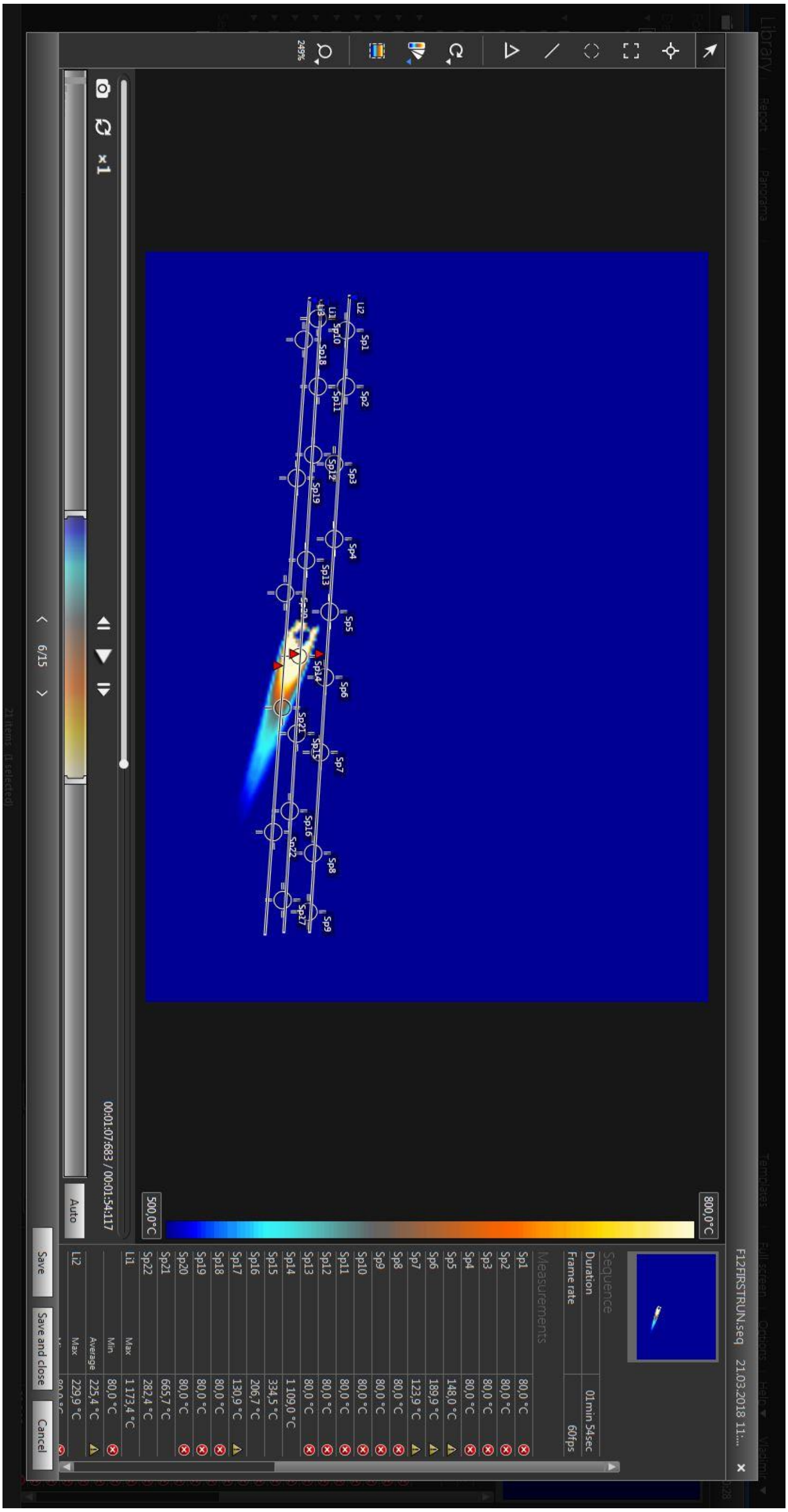
Fillet weld 10mm, 2ND RUN



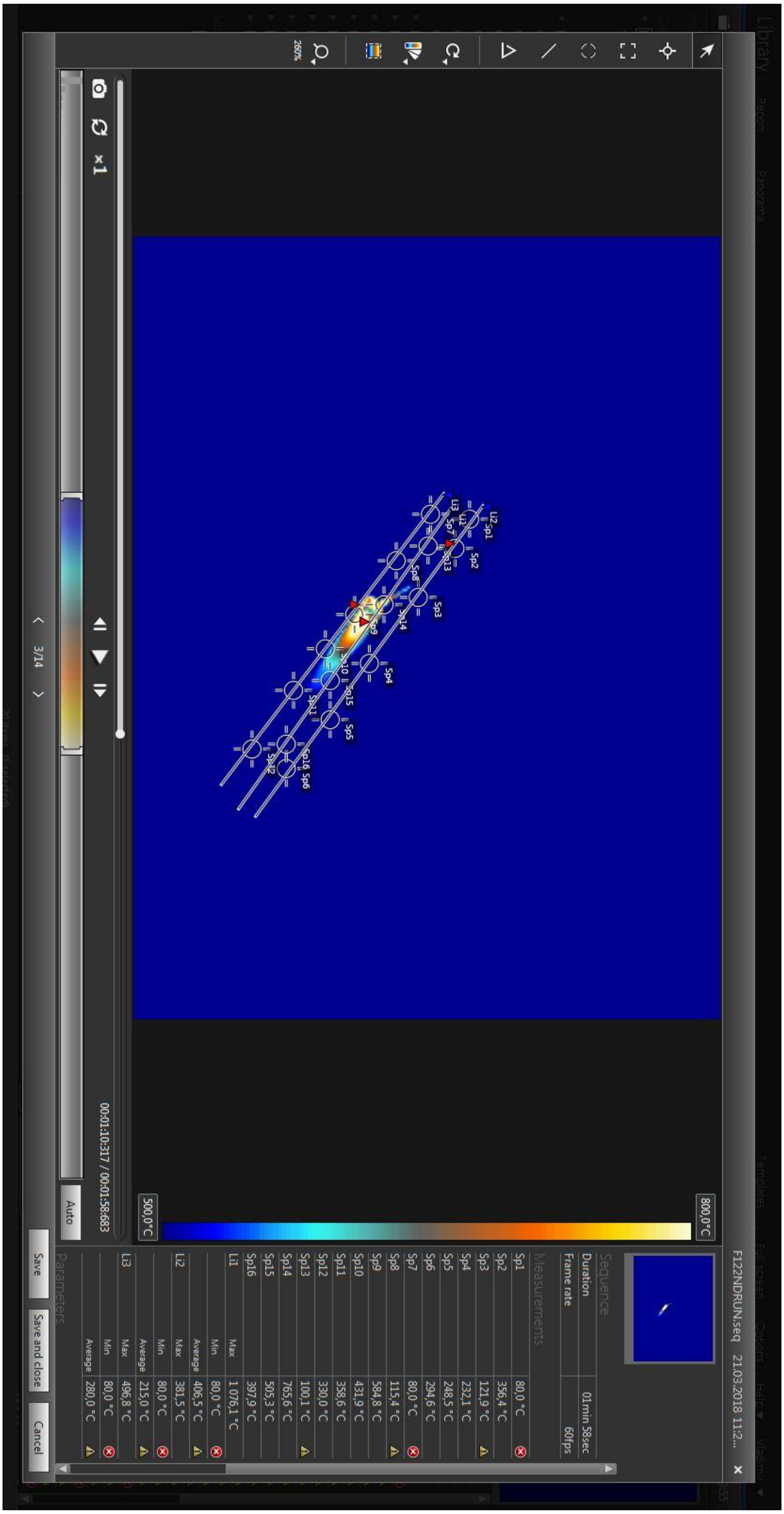
Fillet weld 10mm, 3RD RUN



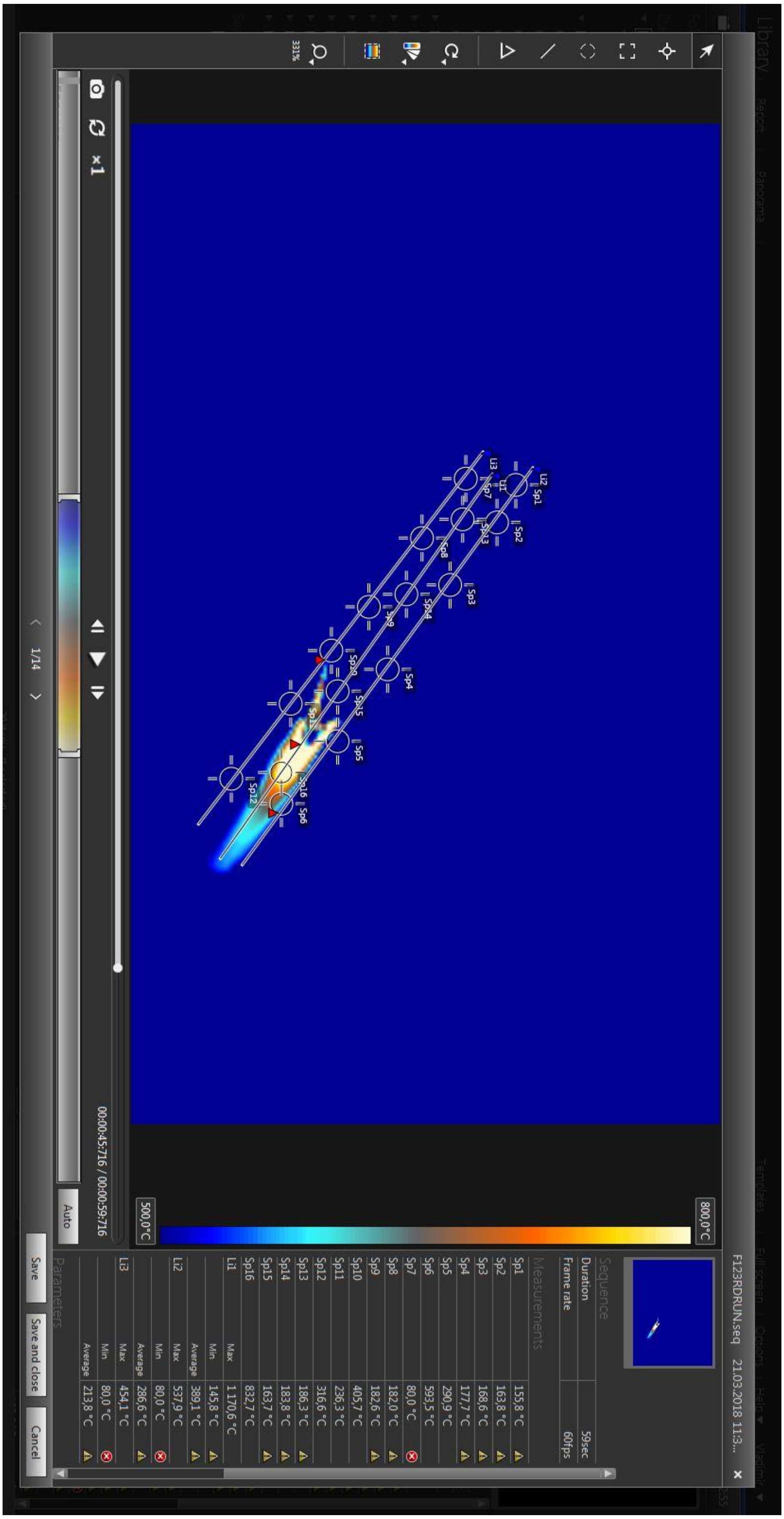
Fillet weld 12mm, 1ST. RUN (F12)



Fillet weld 12mm, 2ND RUN

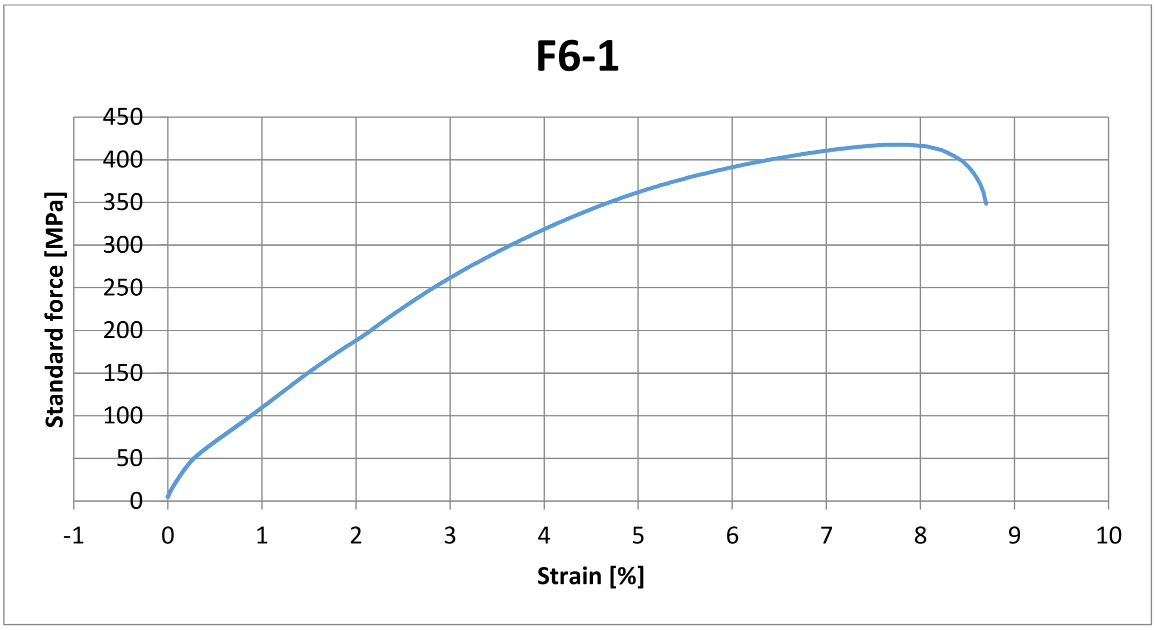


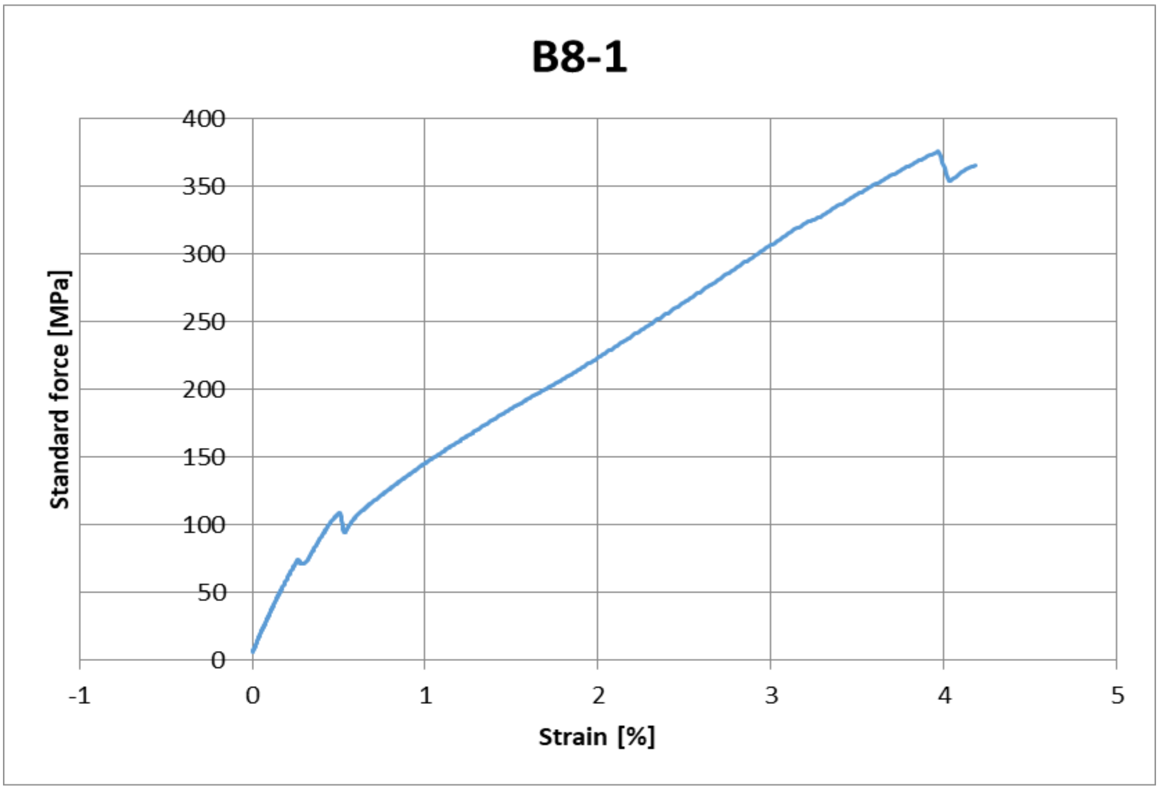
Fillet weld 12mm, 3[RD] RUN

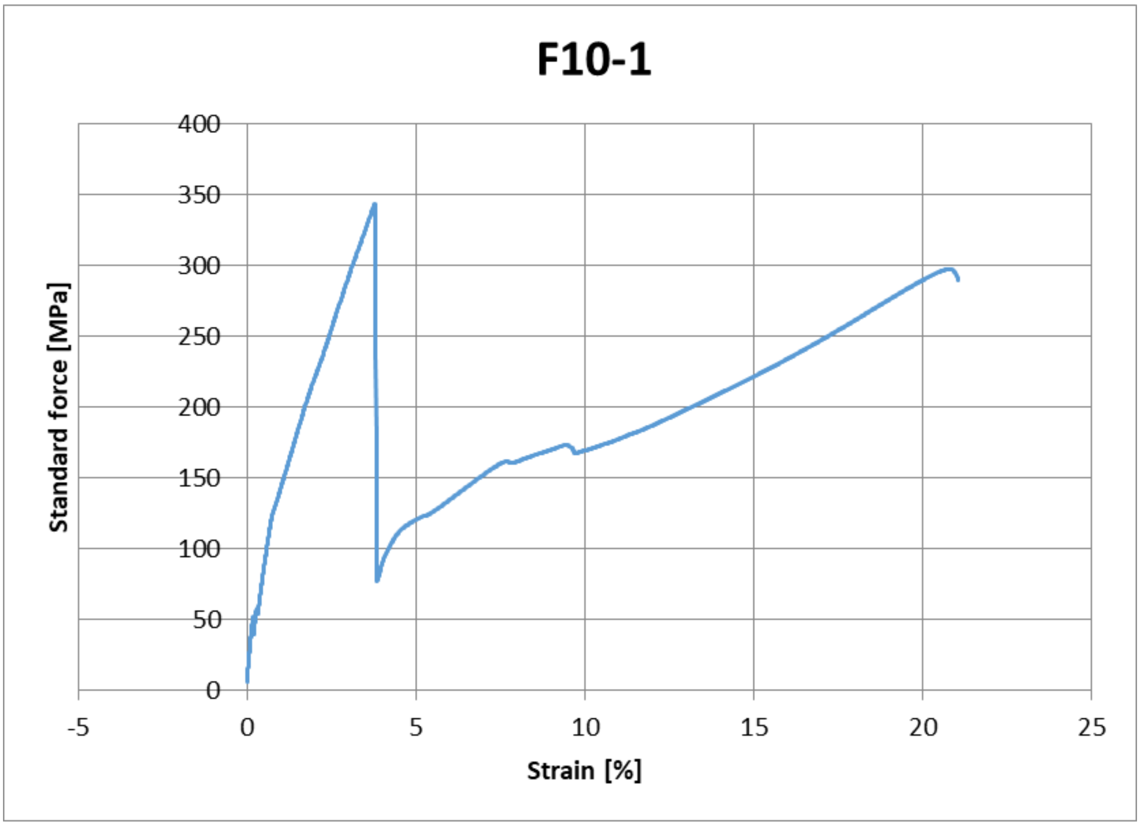


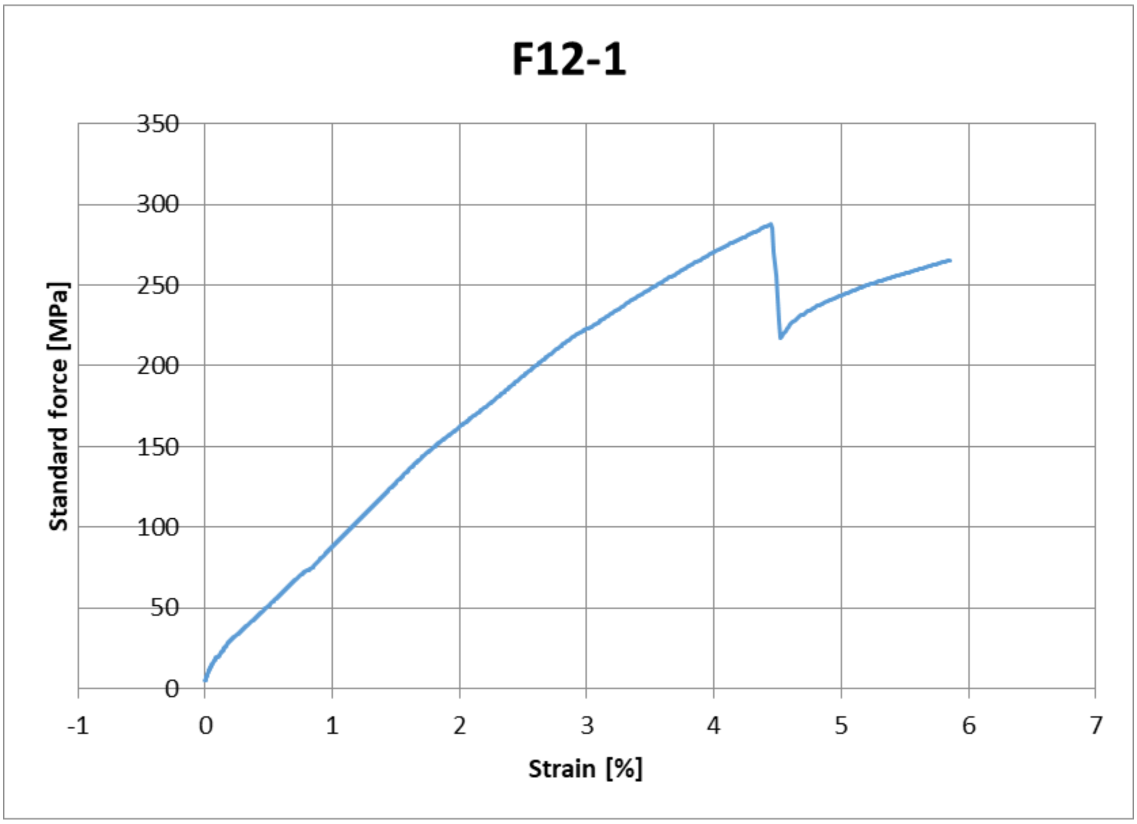
Appendix 2

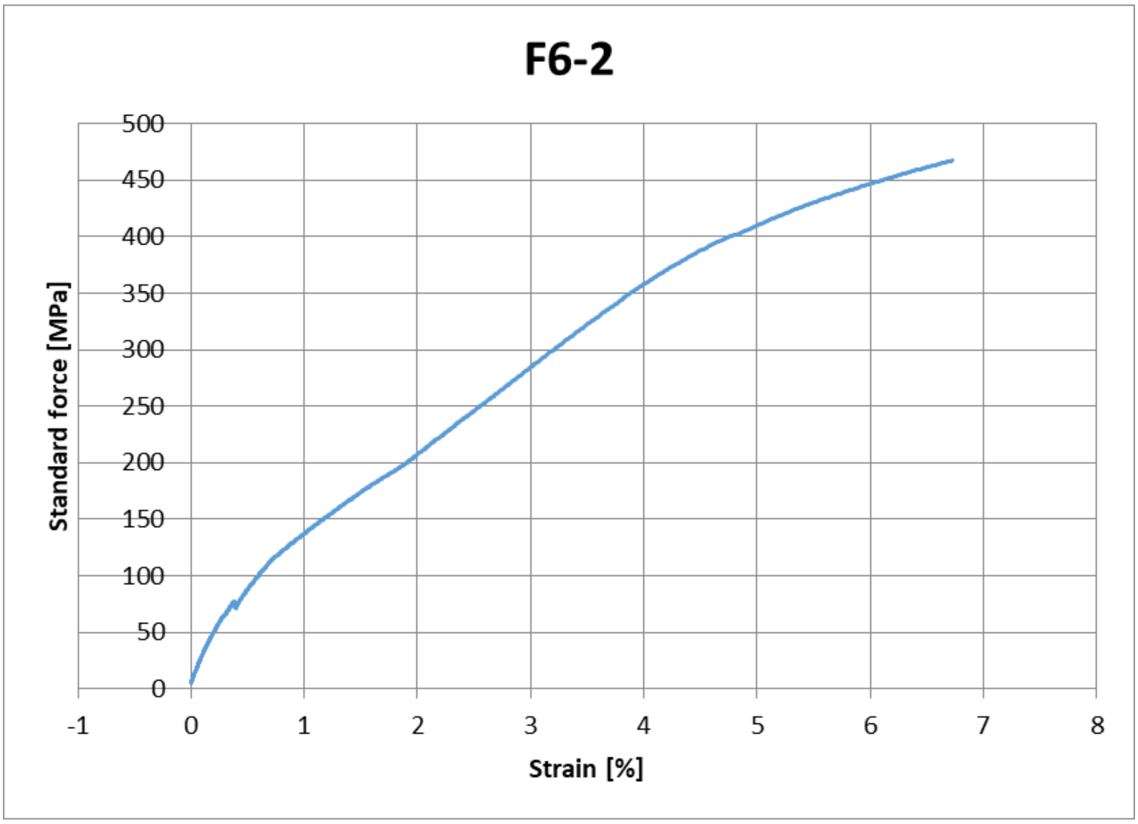
TENSILE TEST GRAPHS

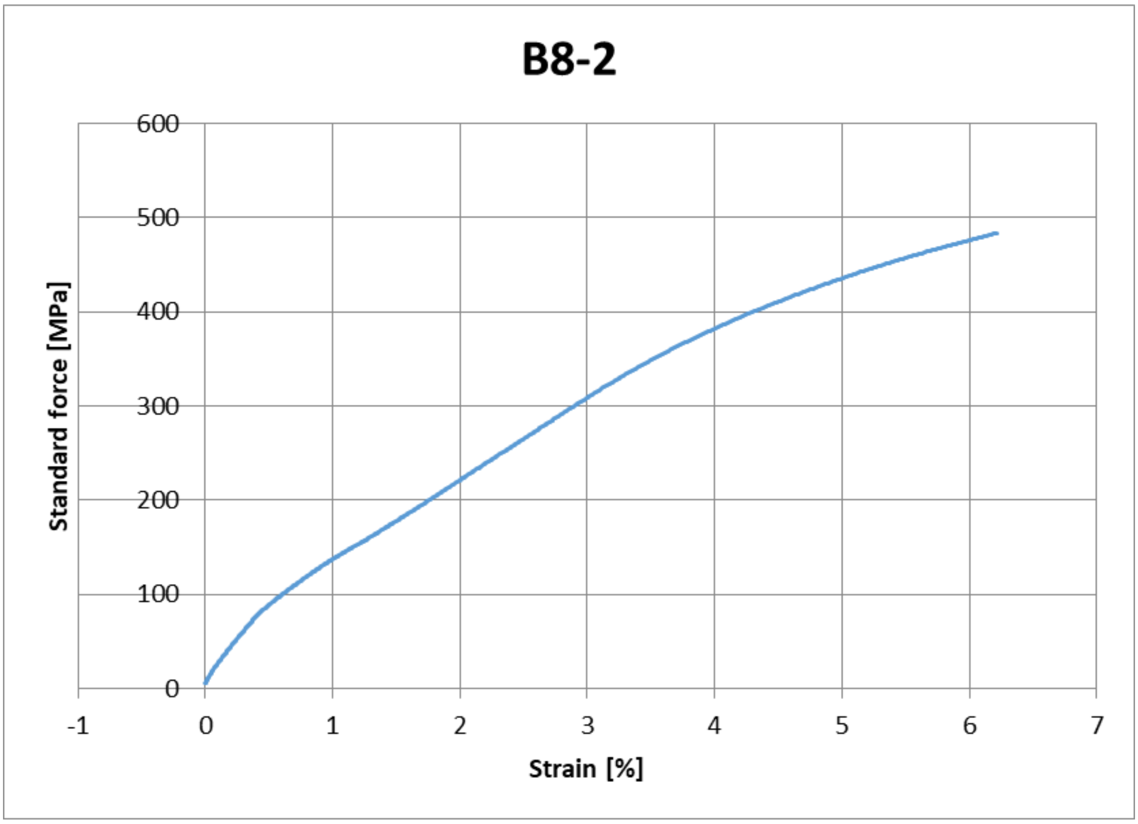


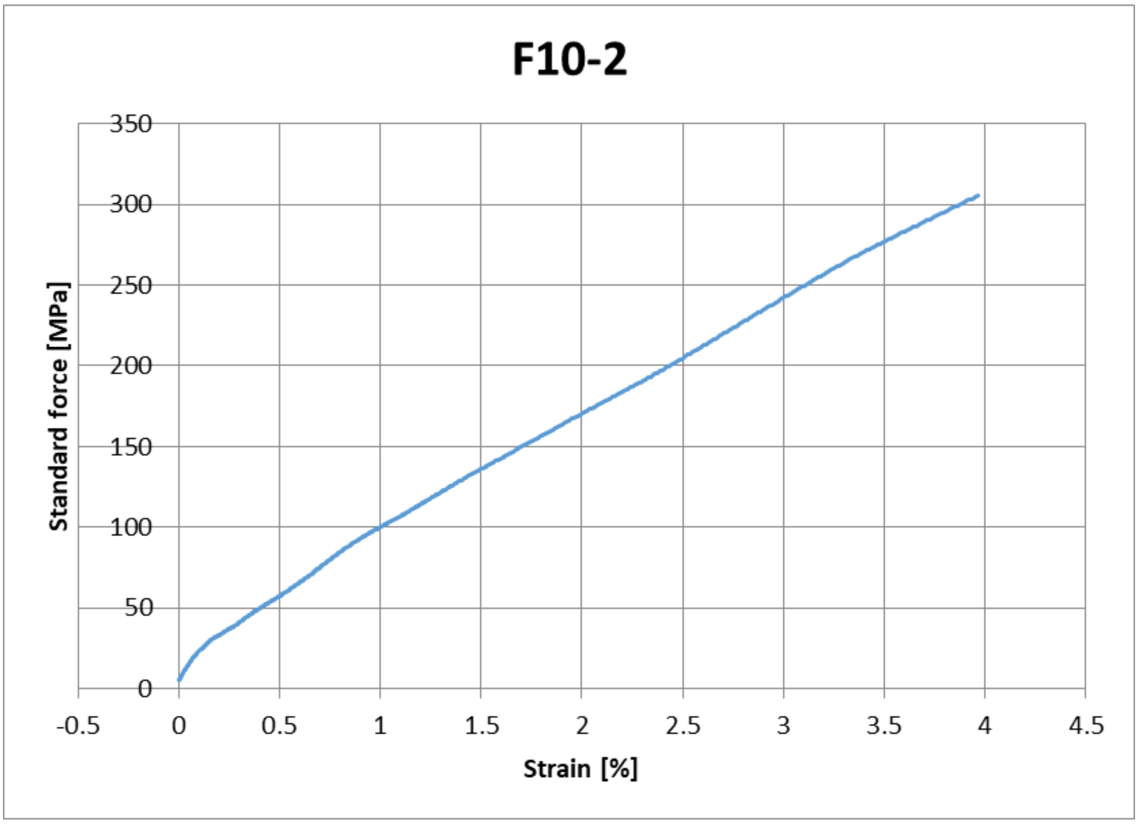


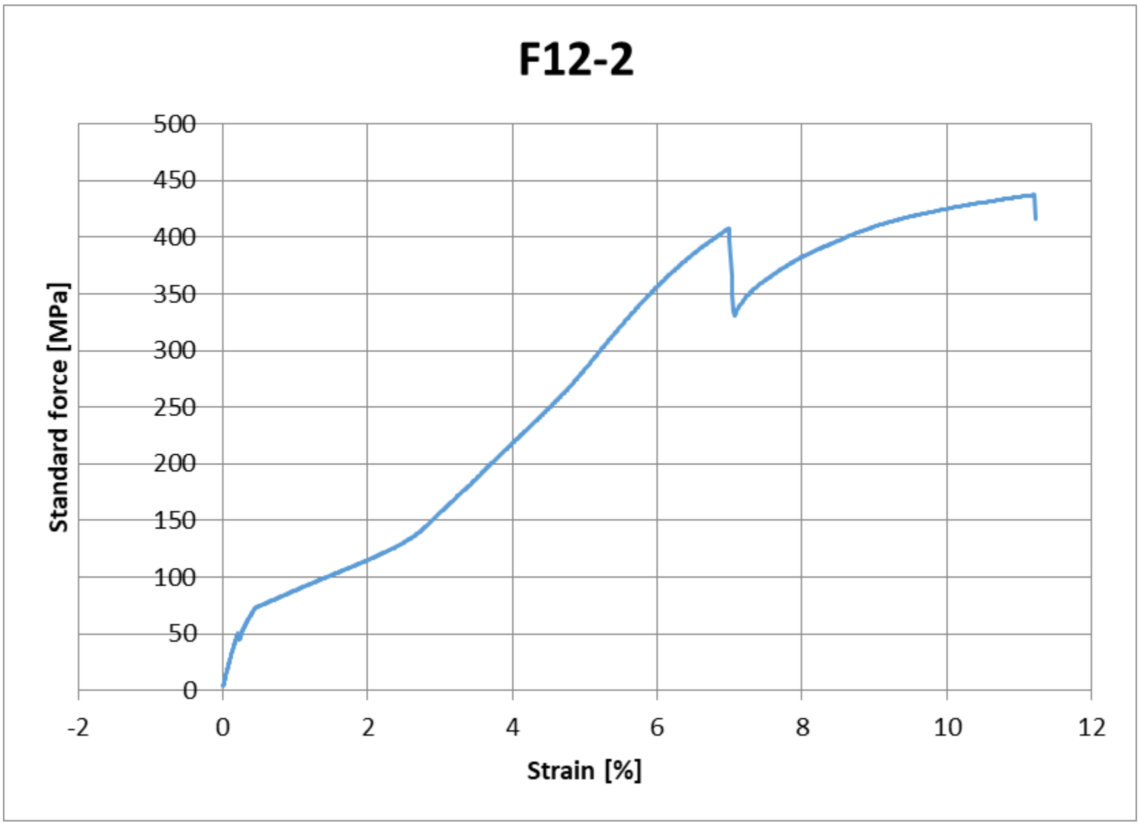

F10-1
Standard force [MPa]
400
350
300
250
200
150
100
50
0
-5
0
5
10
15
20
25
Strain [%]


F12-1
Standard force [MPa]
350
300
250
200
150
100
50
0
-1
0
1
2
3
4
5
6
7
Strain [%]


F6-2
Standard force [MPa]
500
450
400
350
300
250
200
150
100
50
0
-1
0
1
2
3
4
5
6
7
8
Strain [%]


B8-2
Standard force [MPa]
600
500
400
300
200
100
0
-1
0
1
2
3
4
5
6
7
Strain [%]


F10-2
Standard force [MPa]
350
300
250
200
150
100
50
0
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Strain [%]

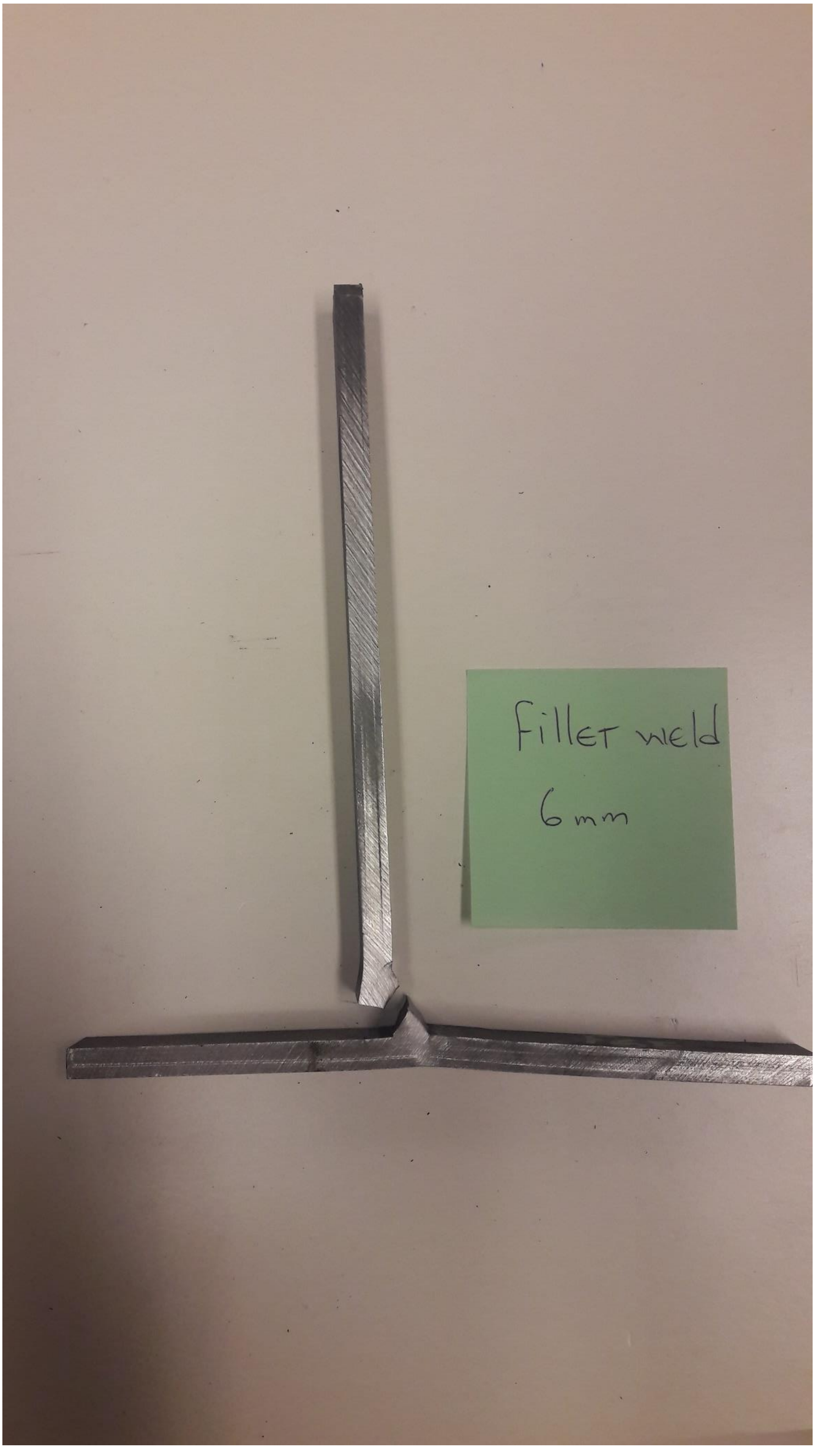

F12-2
Standard force [MPa]
500
450
400
350
300
250
200
150
100
50
0
-2
0
2
4
6
8
10
12
Strain [%]

Appendix 3

FAILURE MODES

Fillet weld 6mm (F6-1)

Fillet weld 6mm (F6-2)



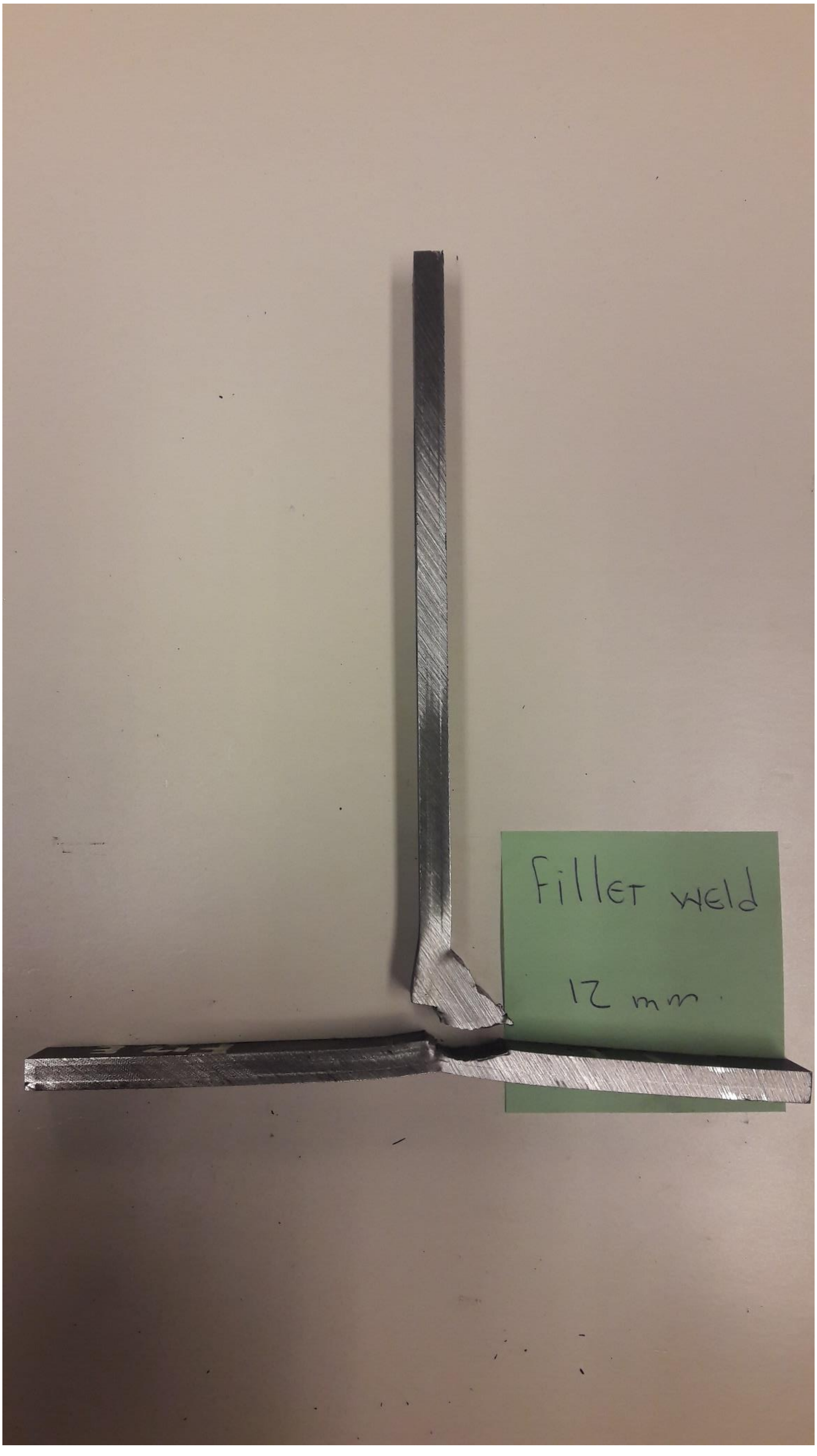
Butt weld 8mm (B8-1)

Butt weld 8mm (B8-2)

Fillet weld 10mm (F10-1)

Fillet weld 10mm (F10-2)

Fillet weld 12mm (F12-1)



Fillet weld 12mm (F12-2)